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MANUFACTURING TECHNOLOGY FOR HIGH VOLTAGE POWER SUPPLIES (HVPS)

Volume I - Program Summary

Northrop Grumman Corporation
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This technical report has been reviewed and is approved for publication.

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13. ABSTRACT
This report is the culmination of a multi-year manufacturing technology program sponsored by the Electronics Division of Wright Laboratory Manufacturing Technology Directorate (WL/MTM). The program was jointly conducted by Northrop Grumman Electronics and Integration Division as the prime contractor and Hughes Aircraft Company Technology Support Division as the principal subcontractor. The thrust of this program was to improve the reliability of High Voltage Power Supplies (HVPS). This was accomplished by conducting a comprehensive evaluation of the materials, components and processes used to produce HVPS. To demonstrate the benefits of the program the lessons learned were incorporated into two existing HVPS, ALQ-135 and AMRAAM. Several of these upgraded high voltage assemblies were fabricated and tested to measure the benefits resulting from the changes.

The report is published in four volumes. The first volume is a summary of the technical activity and highlights of the program. The remaining three volumes provide the specific program and procedural details and reference information generated in performance of the effort. This report, Volume I - Program Summary, contains an executive summary and a description of the results of the material, component and process characterization. At the end of each technical area, a cross reference is provided to related material in the other three volumes.

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FINAL REPORT

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FINAL REPORT

1.0 Introduction

This report is the culmination of a multi-year manufacturing technology program sponsored by the Electronics Division of Wright Laboratory Manufacturing Technology Directorate(WL/MTM). The program was jointly conducted by Northrop Grumman Electronics and Integration Division as the prime contractor and Hughes Aircraft Company Technology Support Division as the principal subcontractor. The thrust of this program was to improve the reliability of High Voltage Power Supplies(HVPS). This was accomplished by conducting a comprehensive evaluation of the materials, components and processes used to produce HVPS. To demonstrate the benefits of the program, the lessons learned were incorporated into two existing HVPS, ALQ-135 and AMRAAM. Several of these upgraded high voltage assemblies were fabricated and tested to measure the benefits resulting from the changes.

The report is published in four volumes. The first volume is a summary of the technical activity and highlights of the program. The remaining three volumes provide the specific program and procedural details and reference information generated in performance of the effort.

The following lists the general content of each volume:

Volume 1, Program Summary, contains an executive summary and a description of the results of the material, component and process characterization. At the end of each technical area, a cross reference is provided to related material in the other three volumes.

Volume 2, Program Details, gives introductory and background information, the approach used, design/development considerations and general information for use by High Voltage Power Supply designers and manufacturers.

Volume 3, Procedural Details, contains procedures on how to perform the various component, material and process evaluations, and gives results obtained from the Northrop Grumman/Hughes Aircraft Company efforts. The Volume 3 procedures are basically stand alone documents and have been numbered as such. They can be referenced for specific areas of interest or treatment of problems; however, when reference is made to Model Test Structures, Volume 4 should be viewed for specific construction details.

Volume 4, Reference Information, contains specific construction details on Model Test Structures used throughout the program as well as test results obtained from the various material and component studies.

2.0 Acknowledgment

We wish to acknowledge the support and guidance of Wright Laboratories project manager M. Price and consultant W. Dunbar for suggestions and critiques of our various presentations, and to further recognize GRC International, Inc. for their coordinating role in this effort.

3.0 Objective

High Voltage Power Supplies (HVPS) have been identified by various Department of Defense entities as a major cause of failure in all systems which use them. This long standing concern is exacerbated by the continuing needs of newer systems for higher power in smaller spaces. The objective of this program was to attack the causes of HVPS failures by developing a better understanding of the basic ingredients that are used in their manufacture.

4.0 Approach

The program consisted of two parts: (1) Improvements to materials, components and processes (identified as phase 1) and (2) incorporation of improvements into hardware for subsequent test and evaluation (identified as phase 2 for Northrop Grumman and phase 3 for Hughes). Phase 1 was planned and tracked using a Process and Product Improvement Plan (PPIP). The plan was periodically updated as lessons learned from the program required changes in program direction.

The focus of Northrop Grumman efforts was on improvements to the HVPS employed in the ALQ-135 Electronic Countermeasures (ECM) system. This power supply is a 12KV, 1800 watt, silicone encapsulated system. Hughes selected the high voltage power supply from the AMRAAM radar (15KV, 1000 watt, epoxy encapsulated) as the focus of improvement efforts. Both systems are in production with sufficient schedule remaining to introduce upgrades from this program. Furthermore, commonality of improvements introduced to these ECM and radar systems are expected to be equally applicable to all dry encapsulant high voltage power supplies used in aerospace systems.

To quantify the results obtained, the HVPS from the ALQ-135 was cost and performance baselined early in the program. The phase 2 testing was conducted directly on the upgraded high voltage assembly from this system.

In the 1987 Airborne Electronics Production Base Analysis, conducted for the Aeronautic System Center and Wright Patterson AFB, HVPSs were identified as a significant problem in terms of reliability and overall performance acceptability. Virtually all program offices surveyed as a part of the study indicated that HVPSs were a reliability issue. In November 1987, the Electronics Division of Wright Laboratory's Manufacturing Technology Directorate (WL/MTM) conducted a HVPS Workshop. The conclusion of the workshop was that material, component and process technology enhancements were needed for HVPSs.

HVPS is not a "glamour" electronic technology. As a result there is not a steady influx of skilled technicians, engineers, and planning specialists who have more than a rudimentary understanding of the critical nature of HVPS manufacturing. This is further exasperated by a lack of material knowledge for HVPS characterization documentation, less than optimum component quality and reliability, and lack of overall test expertise.

The electronic requirements of newer aircraft are increasing almost at the same rate as the allocated volume and weight for the HVPSs are decreasing. In a manufacturing sense, these increasing levels of voltage and power require more definitive specifications accompanied by better design and manufacturing processes, stringent tolerance and interface control, better reliability simulation/modeling and more knowledge of electric and magnetic field stresses.

As a result of the workshop, WL/MTM initiated this Manufacturing Technology for HVPS program. The program was awarded in April 1989. The thrust of the program was to characterize the materials, components and processes used in the manufacture of HVPSs.

Note: The terms high voltage power supply and high voltage assembly are used interchangeably throughout this report; however, the scope of work was limited to the high voltage portions of the power supply ie., the high voltage encapsulated assembly and associated connectors.

5.0 Executive Summary

To improve the performance and reliability of airborne high voltage power supplies, Northrop Grumman and Hughes jointly conducted detailed evaluations of materials, components and processes used in those supplies. Upgrades incorporating the changes were made to actual hardware produced by the two companies (ALQ-135 ECM system for Northrop Grumman and the AMRAAM radar system for Hughes). Resulting improvements were quantified for the ALQ-135 and are shown in Table 5-1. Additionally, the program resulted in several notable developments: A "Dock To Stock" agreement with silicone supplier Grace Specialty Products which results in received product going immediately to stock; the development of a methodology, Quality Function Deployment, that can serve as the basis for performing a comprehensive evaluation of any high voltage power supply; and, the tabulation of program results in Volumes 2 through 4 of this report, Manufacturing Guidelines For High Voltage Power Supplies, which can serve as a useful primer for the high voltage community. These volumes also give numerous construction insights and test techniques as well as providing statistical analysis and test results. We recommend that Volumes 2 through 4 of these guidelines be used as reference material for designing and assessing HVPS.

5.1 Materials

5.1.1 Silicones

Initial evaluation of Grace Specialty Polymers Silicone 4952N (commonly used by Northrop Grumman as a high voltage encapsulant) for its characteristic physical properties disclosed inconsistencies in measured data between Grace and Northrop Grumman as well as batch to batch variation. The objective to thoroughly characterize this material was set aside to first establish site and batch consistency of measurement. With support from the Northwestern University Materials Department, it was determined that typical measuring techniques such as described in Mil Spec and ASTM procedures did not properly account for the unique characteristics of an elastomer. A concerted effort involving standardization of test fixturing, standardization of test technique and verification of physical properties by third party testing laboratories significantly closed the discrepancy gap.

Statistically significant batches of material were evaluated resulting in two physical properties, Tear Strength and Compressive Modulus, established as defining properties ie., a "measure of consistency" for the material. A "Dock To Stock" purchase document was subsequently created and is now in use. It essentially establishes specification limits on vendor supplied data (such as viscosity, specific gravity, coefficient of thermal expansion, thermal conductivity, tensile and dielectric strength etc.) and defines the two key characteristics, Tear Strength and Compressive Modulus, with both specification limits and statistical process control limits. The latter are measurements made by the supplier and provided with each batch of material. Typically the incoming material is routed directly to stock and quality assurance statisticians record and perform trend analysis on the accompanying data.

		Baseline	Current (1994)	IMPROVEMENT Goal (%)	IMPROVEMENT Actual (%)
Hours to Build	Assembly	69.2	45.4		
	Test	13.1	4.8		
	Total	82.3	50.2	Not set	39%
Hours to Rework	Assembly	4.9	1.98		
	Test	4.8	1.66		
	Total	9.7	3.64	2.4 (75%)	62%
Scrap Cost		$568.	None in 1994	$100. (82%)	100%
Realization Factor	Assembly	1.35	1.12	Not set	17%
MTBF, Hours	Desert Storm (HVPS)	386			
	Stress/Life Testing		1285	(3X)	3.3X

Table 5-1 ALQ-135 Program Improvements

5.1.2 Epoxies

During our characterization studies, the physical, thermal, and electrical properties of seventeen different epoxy encapsulant material candidates were studied. The purpose of these studies was to assemble a consistent set of data on material properties that are important and relevant to HVPS encapsulation - all of which were obtained using well-documented, standard tests. Armed with this data, other workers in the field can select an encapsulant from those in our study that is appropriate for their application. Alternatively, using the same test methods, they could perform tests on a range of other encapsulant candidates, and compare their results to those in our data tables. The data is presented in Section 6.1.2 of this volume and a full analysis of our results is presented in Section 2.6 of Volume 4 of the Design and Manufacturing Guidelines.

We also studied key electrical parameters for epoxies used for transformer encapsulants, employing simple Model Test Structure and Design of Experiments methodology. These studies, with their methods and results, are presented in Section 2.3 of Volume 4 of the Design and Manufacturing Guidelines.

Finally, an issue related to the degree of cure in polymer thermoset materials - specifically Emerson & Cuming Stycast 2651MM - was explored by Dr. Stephen Carr at Northwestern University. This investigation focused on various methods for measuring level of cure and compared the results. Two test methods, Differential Scanning Calorimetry (DSC) and Fourier Transform Infrared (FTIR) proved workable to characterize the extent of cure while two alternate methods, Volume Resistivity and Solvent Swelling, proved impractical. Details of the study are presented in section 6.1.2 of this report.

5.2 Components

5.2.1 High Voltage Connectors

Previous user surveys identified connectors as a high voltage power supply reliability concern. To follow up, connector manufacturer, Reynolds Industries, was subcontracted to study and evaluate a 12 pin 15KVDC rated connector commonly used by Northrop Grumman and others. A test program was devised to exercise the connectors through temperature altitude cycling with high voltage applied (one full cycle takes about 8 hours). Each male-female connector set was attached to Teflon insulated wire to simulate an installed application. Leakage, voltage breakdown, corona and resistance measurements were made periodically during the cycling.

Four test conditions were established: 1. 15KVDC applied 2. 18KVDC (20% overvoltage) applied 3. connectors were unmated and remated as part of the cycling (15KVDC operation) 4. connectors were only partially mated throughout the cycling (15KVDC operation). The latter two conditions are to simulate possible field situations. Breakdown failures varied from non-existent through the first 75

cycles of test condition 1 to numerous failures when subjected to prolonged operation at higher voltage and/or unmating/mating, partially mated operation. Analysis of failures proved quite interesting. In all cases the single biggest cause of failure was shrinkback of the Teflon insulation at the connector interface which subsequently exposed the center conductor and led to arcing. Pre assembly temperature cycling of just the wire helped somewhat but shrinkback could not be eliminated. Further investigation determined that stresses in the wire insulation are induced at the time of extrusion and that this process is the determining factor for later performance when the wire is temperature cycled. Discussions with wire manufacturers indicate the inherent stresses in the insulation can be mitigated with a slower, more controlled extrusion process.

Also noted in the failure analysis was the presence of debris in test condition 3. Recommendations to clean surfaces with isopropyl alcohol were made. Of further interest is that throughout all the test conditions the critical connector noses remained in good shape. Furthermore, corona measurements did not prove useful as a predictor of failure.

5.2.2 Capacitors

5.2.2.1 Ceramic

In the course of studying surface mount ceramic capacitors a mini workshop of vendors and users agreed that these components are readily being accepted as a commodity item when in fact they can vary significantly. Furthermore, the components are subject to arbitrary and inconsistent acceptance criteria which varies from user to user and vendor to vendor. It was agreed that a strong inspection criteria should be established prior to use.

Sonoscan Inc. was contracted to perform acoustic (ultrasound) examination of approximately 400 components prior to mounting on a substrate. The traditional acoustical evaluation consists of a SLAM (Scanning Laser Acoustic Microscope) examination performed at 25 to 30 Mhz. The examination is intended to reveal cracks, voids and delaminations which would impact reliable performance. A second acoustic examination, C-SAM (C-Mode Scanning Acoustic Microscope) was also conducted to verify and serve as a comparison with the SLAM evaluation. The results of the two methods were complimentary but also mutually exclusive with each method revealing a number of different type "flaw" details. The C-SAM method, although more costly, proved to have better sensitivity and was able to identify a greater number of defects. Furthermore, the C-SAM is digitizable for image storage and enhancement. A number of parts were sectioned and the optical information compared with the acoustic. Subsequently, parts with cracks, delaminations and voids over 0.010 inches in diameter were deemed unsuitable for operational use (the latter size limit associated with operating voltage stresses up to 200 volts per mil).

5.2.2.2 Mica

In order to establish standard methods for characterizing mica paper HV capacitors, a "standard evaluation" format was developed for three capacitor types (3kV, 5kV and 10kV) and samples of these were obtained from five different manufacturers. The samples were then characterized to determine their conformance to specification (physical size, capacitance etc.) and to determine their reliability under selected operating conditions. The latter tests included thermal shock and accelerated life testing, coupled with AC and DC corona testing and dielectric withstanding voltage in Freon TF to assess the effects on the capacitors.

The results of the post thermal shock HV tests on the sample capacitors were quite good, and are indicative of generally good quality in the capacitors tested. AC corona levels including both CIV and CEV values varied less than 20 percent for all the capacitors tested, from all manufacturers. DC corona levels were essentially unchanged from all devices from all manufacturers, and no DWV failures occurred either before or after thermal shock for any device from any manufacturer.

Failures were observed during accelerated life testing as shown in Table 5.2-1 below. Test conditions and further detailing are in Section 6.2.2.2.

Device Type	MFGR	No. of Failures
3 kV - 22 nF	Cera-Mite	0 (11)
	Custom	1 (12)
	Del	3 (10)
	Reynolds	0 (12)
	Tobe Deutschman	1 (11)
5 kV - 15nF	Cera-Mite	0 (12)
	Custom	0 (12)
10 kV - 10 nF	Cera-Mite	0 (04*)
	Custom	0 (12)
	Del	9 (09)
	Reynolds	1 (12)
	Tobe Deutschman	0 (12)

Table 5.2-1 Confirmed Failures Occurring During 1100 Hours Of Accelerated Life Testing Of Mica Capacitors

( ) denotes number of devices starting test

* 8 units not started due to equipment capacity

5.2.3 Diodes

Diodes are among the most important components of HVPSs. For this reason extensive characterization was undertaken as part of this program. The purposes of the characterization was twofold: first, to demonstrate the type of tests we believe should be performed on diodes and, second, to assemble a self-consistent set of data on diode characteristics that are important and relevant to the functioning of a HVPS. These data are reported in the remaining volumes of the Design and Manufacturing Guidelines.

In Section 1.5.1 of Volume 3 of the Design and Manufacturing Guidelines we present our construction reviews of high voltage diodes, and show the widely varying results obtained from diodes manufactured by six different vendors. From these results, it is clear that diode construction varies greatly from manufacturer to manufacturer, from part to part, and further varies in ways that can be very important to the functioning and reliability of the HVPS. The Guidelines also provide a methodology for performing a construction review on diodes that is our recommendation for others to use.

In Section 1.5.2 of Volume 3 of the Design and Manufacturing Guidelines we present the results of an electrical evaluation of eleven different diodes from six different manufacturers. As in the case of the construction review, variations in the electrical properties of the diodes were observed that would be significant for individual applications.

While most of the characterization methods described in these sections are standard methods that are relatively easy for other workers to reliably duplicate. However one test method, reverse recovery time (Trr) deserves special attention since it is highly dependent upon the precise manner that the testing is performed. Careful attention must be paid to the set-up for conducting this test and as the test is repeated over time, the experimental procedures be replicated as exactly as possible. If care is not taken there is a distinct likelihood that data collected on one occasion may not be directly comparable to similar data collected later on. Furthermore, bodies of Trr data taken by different laboratories on the same candidate diodes may not be directly comparable.

Diode selection and evaluation processes are good candidates to use the Quality Function Deployment methodology described in Appendix 1-1 of Volume 2 of the Design and Manufacturing Guidelines. This methodology will allow the correct candidate selection for the application in a concise, objective manner rather than a subjective or intuitive evaluation often obtained from limited characterization studies.

The following is a cross reference guide to specific program details, procedural details and reference information in Volumes 3 and 4 that relate to diodes:

Volume 3 Procedural Details

Section 1.5 Diode Test Methodology

This section provides a method for a construction review (Section 1.5.1) and the results of electrical and environmental evaluations (Section 1.5.2).

Volume 4 Reference Information

Section 1.5 Diode Heat Transfer Test Structure

This section shows a model test structure (MTS) that was used to evaluate the heat path mechanism of various diode constructions.

Section 2.5 Evaluation of High Voltage Diodes Using Model Test Structures

This section provides the results of thermal evaluation of glass encased and molded plastic package diodes using the MTS methodology provided in section 1.5 above.

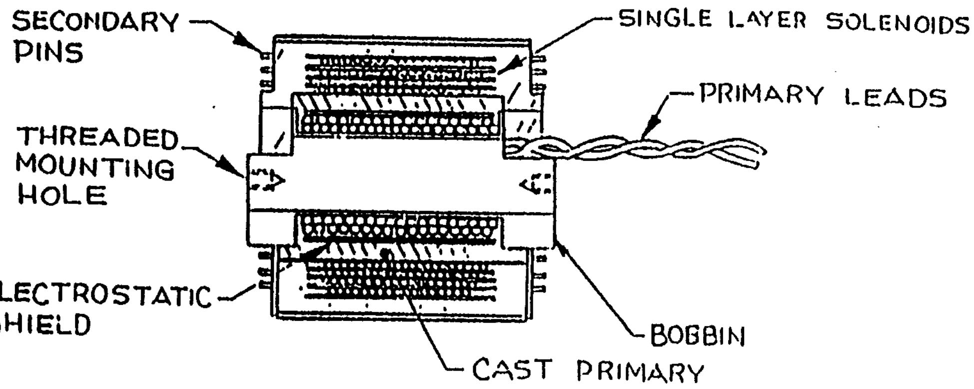
5.2.4 High Voltage transformers

One of the main reliability concerns in compact, high power, high voltage power supplies is the output transformer. This is the active power processing unit for the load and even with efficiencies above 90 percent, the heat dissipation is substantial. Typically the resulting high operating temperatures require that thermal paths and heat sinking be given equal consideration with voltage stand-off requirements when designing the insulation system. Furthermore, high operating temperatures require careful monitoring to prevent core saturation. The electrical design requires sufficient robustness for long life but tempered to be within the allowed space requirements. All these factors result in a relatively complex, costly unit and mitigate using significant quantities of the actual transformer for any design evaluation program. Model test structures closely simulating the actual transformer and allowing electrical activation to achieve transformer operating stresses were developed for the reliability investigations conducted in this program. These model test structures greatly reduced costs associated with both construction and testing. Figure 5.2-1 illustrates the Northrop Grumman output transformer and one of the model test structures used to evaluate a significant problem - wire breakage at the bend radius where the secondary wires enter the header pins. This bend radius provides stress relief for the wire to withstand encapsulant movement under environmental conditions. Unfortunately, stripping the wire in preparation for soldering, cold working to create the bend radius and then proceeding with the soldering operation creates stresses in the wire that impact its reliability.

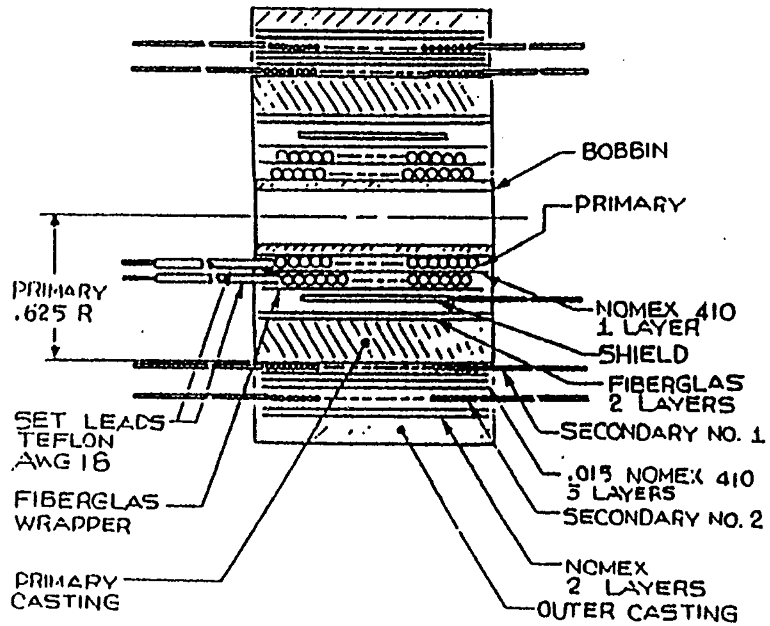
A test program using statistically significant quantities of model test structures was conducted to evaluate four wire stripping techniques. The techniques ranged from mechanical scraping and Thermal (hot) wire removal of insulation on 200C rated wire to lower temperature soldering iron and soldering pot stripping of 150C and 130C insulated wire. The program was established after reliability

analysis using conventional metallurgical/SEM techniques revealed wire fatigue as the cause of several field failures and therefore the wire pre-treatment was suspect. The program results clearly indicated that using the lowest rated (130C) wire in conjunction with solder pot stripping produced superior reliability. Figure 5.2-2 shows the key test phases of the program. All test structures were electrically operated to achieve 150C internal operating temperatures and MTBF data was obtained by temperature cycling the structures to failure. The numbers in the boxes are the temperature rating of the wire with "ss" signifying solder strippable. It should be noted that using 130C rated wire in a 150C operating environment could have long term deleterious effects on the wire insulation; however, since insulation rating is based on 10,000 hours in a condition of crossed wires with pressure applied, the likelihood of failure in our test structure was considered extremely low. In fact no problems were encountered in the testing program.

A second area of operational concern with transformers is the inability of parallel windings to equally share current at high frequencies. This is related to changes in the coefficient of coupling with frequency. Parallel windings are popularly used to share high currents while retaining the mechanical flexibility of smaller wire sizes. In compact high voltage airborne applications, for example, small size is a driving consideration. Measurements made in each leg of the parallel windings show severe current and phase imbalances - often to the point of either having one leg carry almost all the current or the existence of circulating currents in the parallel legs. These conditions produce hot spot locations and subsequently lead to failure. Section 6.2.4.2 gives the results of both Spice simulation and actual measurements showing the unequal sharing and makes some suggestions for improving current sharing. As a practical matter, both Northrop Grumman and Hughes no longer use parallel winding structures in their high voltage transformers.



TYPICAL HIGH VOLTAGE TRANSFORMER



TEST COIL

Figure 5.2-1 High Voltage Transformer and Test Structure

PHASE 2 WIRE TEST 150 C	SCRAPPED WIRE 200	THERMAL STRIPPED 200	SOLDER POT 130 SS	THERMAL STRIPPED ENCLOSED 200
MTBF =>	363	247	1,367	471
PHASE 3 WIRE TEST 150 C		THERMAL STRIPPED 200	SOLDER POT 130 SS	
MTBF =>		592	1,517	
PHASE 4 WIRE TEST 150 C	SOLDER POT 130 SS	IRON STRIPPED 150 SS	IRON STRIPPED NO S.R. 150 SS	SOLDER POT 150 SS
MTBF =>	878	502	408	678
PHASE 5 WIRE TEST 150 C	SOLDER POT 130 SS	IRON STRIPPED 130 SS	SOLDER POT 150 SS	IRON STRIPPED 150 SS
MTBF =>	1633	1278	690	716

Figure 5.2-2 Transformer Test Program

5.3 Processes

The results of this program produced a number of changes to manufacturing processes that enhanced reliability, improved yield and reduced rework. These changes include optimizing the transformer wire stripping process in conjunction with use of a lower temperature rated wire, specifying the amount of shrinkback allowable for Teflon wire, establishing two key parameters of Silicone as "defining properties" for rating the material (and the subsequent use of Statistical Process Control for those parameters) as well as a "Dock To Stock" arrangement with Silicone supplier, Grace Specialty Products. Other changes include introducing slip surfaces (via Teflon coating) in certain encapsulated assembly locations to allow encapsulant movement - thus preventing stress build up and subsequent cracking, establishing a common environmental stress cycle for measuring life performance of subassemblies, and use of C-Slam ultrasound technology as a diagnostic tool.

In addition to direct process changes as described above, there is another avenue that can play a significant role in achieving performance and reliability objectives. This avenue is to perform concurrent engineering as part of the design process to forestall having to go back and correct or upgrade parts and processes as a result of poor performance. The relatively high failure rates for high voltage power supplies during the development process, and in service, are evidence of the fact that they are very difficult products to engineer and manufacture. Deceptively simple circuit diagrams belie the extreme difficulty of simultaneously satisfying often conflicting requirements that include small size, light weight low cost, high voltage, high power output, high reliability, and low electro-magnetic emanations. Critical variables in the power supply, such as component and material properties, heat, voltage stress, component and conductor locations, shielding etc., can interact in complex ways that can be difficult to anticipate during the development process.

In most cases, successful HVPS development programs require that teams of experts in various disciplines (electrical, packaging, materials, components, processing and test) work together to contribute to the HVPS design. Yet experience shows that such teams do not usually function in an integrated way, but tend to function as groups of specialists loosely bound by the project's objective. These observations led to the realization that a new methodology was needed to assist these teams in working together more effectively throughout the HVPS development process. We chose to develop the technique of Quality Function Deployment (QFD) as the principal concurrent engineering tool for the HVPS program, and created a set of QFD charts that are customized specifically for the HVPS development process. The QFD methodology for HVPSs is basically a technique that relates the HVPSs requirements to the means that will be used to achieve them. The QFD process is used to match the "whats" and "hows" at all conceptual levels of the HVPS, from the matching of the top level requirements for a high voltage module

with detailed packaging approaches to the lowest level where an individual electronic component or encapsulation material is selected to fulfill a specific function. We have found that this process provides a mechanism by which all of the members of the concurrent engineering team can contribute to all of the key selections made during HVPS development, and results in a far superior product being produced in a far shorter period of time.

When the QFD process raises questions about a particular candidate approach, component, material, etc., the concurrent engineering techniques of Model Test Structures, coupled with Design of Experiments, can be used to answer those questions, and move the development process toward its conclusion. These three techniques are discussed in more detail in Section 6.3 of this report and in Appendix 1-1 and Section 3.2 of Volume 2 of the Manufacturing Guidelines.

6.0 Results

6.1 Materials

6.1.1 Silicones

INTRODUCTION

Since silicone elastomers are an important high voltage packaging material at Northrop Grumman, this class of materials occupied a significant portion of the material study effort. The already established baseline of experience provided a firm starting point for the program and the existing facilities and production programs provided the means to verify the true utility of the ManTech findings.

Previous contractor material surveys listed several silicone products of interest from a number of formulators. Since not all could be (or should be) investigated the list was screened down to include representatives of major classes or types of silicones. Specifically, it was decided to select the following products and formulators.

Product	Class	Formulator
Sylastic E	Addition cured for fast, deep section applications. Filled.	Dow Corning
RTV-615	Addition cured. Unfilled.	General Elec.
ECCOSIL 4952N	Condensation cured with very heavy filling.	Formerly, Emerson & Cuming Now, Grace Specialty Polymers
ECCOSIL 2650-5	Addition cured and primerless. Very heavily filled. Experimental.	Emerson & Cuming Grace

The entire material evaluation effort, including the selection of the above materials, followed a testing program flow chart established early in the ManTech program. This chart is shown in Figure 6.1-1.

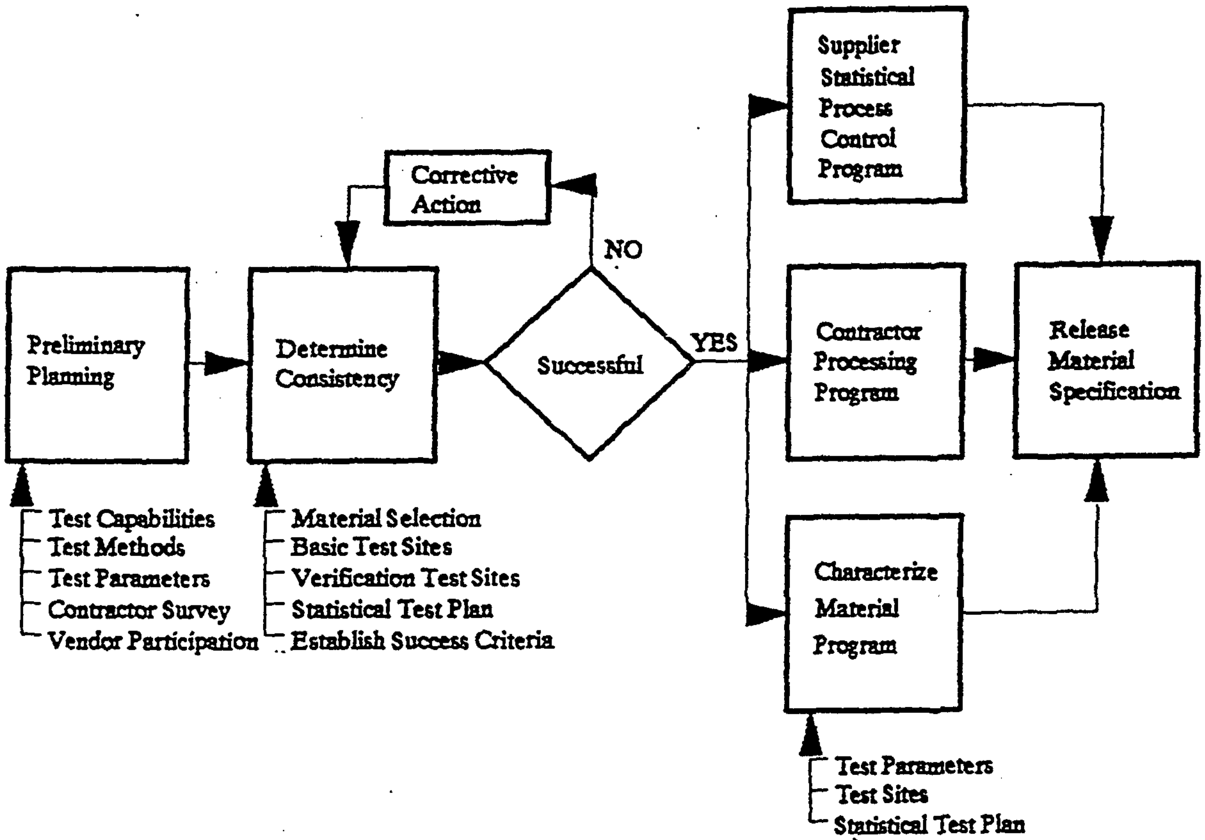


Figure 6.1-1 Material Testing Flow Chart

The issues of test methods, test parameters, test site consistency and test planning were addressed first and will be discussed separately.

An important feature illustrated by the flow chart in Figure 6.1-1 is the separation of material properties into Consistency and Characterization attributes. While characterization of properties is critical to an engineering design program, consistency is of critical importance to a manufacturing application. Note that a determination of consistency precedes characterization. This is not the usual sequence of events seen in industry - a material is usually selected based on engineering criteria and the production facility is forced to "learn how to live with it". The terms Consistency and Characterization are defined as follows.

> Consistency is exactly that, consistent properties, batch-to-batch. For this program that meant selecting temperature independent properties, representative of all properties, which could be specified, monitored and controlled in a cost effective manner.
>
> Characterization concerns the temperature dependent properties of materials required for a comprehensive engineering evaluation. This type of effort initially establishes properties for stress modeling usage, however, it also becomes the basis for possible future programs of material improvement or replacement.

These two distinctly different classes of attributes will be discussed separately below.

During mid-program it was decided to use the results of the property measurement effort in an attempt to establish a dock-to-stock acquisition arrangement with a key Northrop Grumman supplier. Such an arrangement requires trust and agreement between supplier and contractor which flies in the face of the usual adversarial approach. This dock-to-stock arrangement was recently concluded between Northrop Grumman and Grace Specialty Polymers with ECCOSIL 4952N after an evolutionary and frequently feisty three year period. This effort will also be discussed separately below.

SILICONE TESTING RELATED MATTERS

The usual procedure for establishing material property values is to deliver some material to a test site, either internal or outside, and ask that site to "characterize" the material. These values are then used to develop a specification for acquiring and processing the material. That is exactly what was done for this ManTech program per Figure 6.1-1 but with the added ingredient of establishing a firm statistical basis for first selecting meaningful properties and then meaningful measurement techniques.

Figure 6.1-2 will serve to illustrate some statistical concerns. Material properties are represented in Figure 6.1-2 by the statistical distribution labeled Strength Distribution. The environmental operating stresses imposed by an equipment application is labeled

Stress Distribution. The object of a measurement program is to define these strengths and stresses such that the "Trouble Zone", where stresses exceed strengths, is known with high confidence. If this is not done, production yield and reliability problems could easily be (and frequently are) the results.

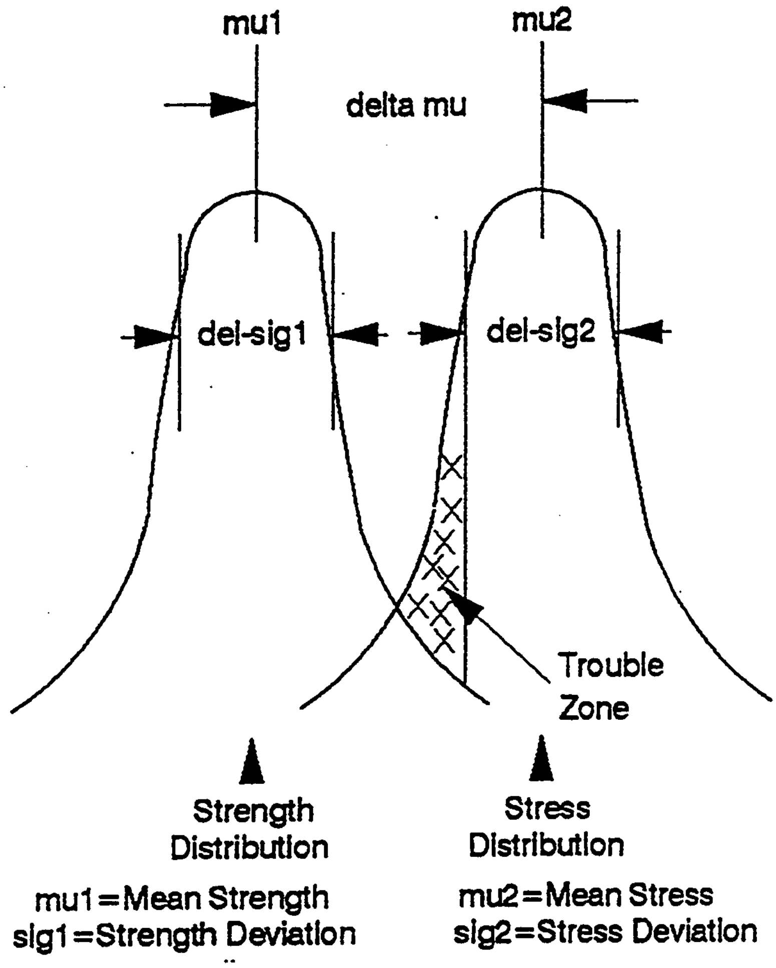


Figure 6.1-2 Statistical Influences

Actual measurements accumulated by Northrop Grumman over several years of time will illustrate the extent of this issue as it effects the use of ECCOSIL 4952N. Figure 6.1-3 shows the simplified, one dimensional, expression which defines the triaxial stress exerted on a material during shrinkage caused by curing. In fact, this is a three dimensional hydrostatic force but the example still illustrates the sensitivity of the matter.

- $S = Ee/(1 - 2u)$
  - S = TRIAXIAL STRESS (A CALCULATED PROPERTY)
  - E = ELASTIC MODULUS (A MEASURED PROPERTY)
  - e = STRAIN (CALCULATED FROM DIFFERENCES IN CTE)
  - u = POISSON'S RATIO (A MEASURED PROPERTY)
- EFFECT OF POISSON'S RATIO MEASUREMENT
  - FOR u = 0.46, S = 12.5Ee
  - FOR u = 0.48, S = 25Ee

Figure 6.1-3 Triaxial Stress Example

The two measured properties in Figure 6.1-3 are the elastic modulus (E) and Poisson's ratio (u). Note that a four percent change (or error) in u, results in a 100 percent change in the calculated stress. The effect of E measurements is linear.

Figure 6.1-4 illustrates a fundamental error induced when measuring E and u per the normal ASTM D-412 tensile test method. ASTM D-412 measures these properties in the test range shown in Figure 6.1-4. In fact, an actual operating material will never be stressed to these levels. The range of interest is shown in Figure 6.1-4 as the Low Strain Range - or strain in the 0 - 5 percent range. This point is intuitively obvious but frequently overlooked. It is also typical to use strain gauges for measuring both axial and lateral strain. Since the normal strain gauge substrate (usually a polyimide) is stronger than a silicone elastomer such measurements will be grossly in error. Some type of indirect method is required and an optical method is usually employed. The typical optical method is to scribe lines on the item under test and measure length changes with a graduated telescope of some type. Remembering the extreme sensitivity of u, however, in the triaxial stress example this simple technique proved inaccurate to an unacceptable degree.

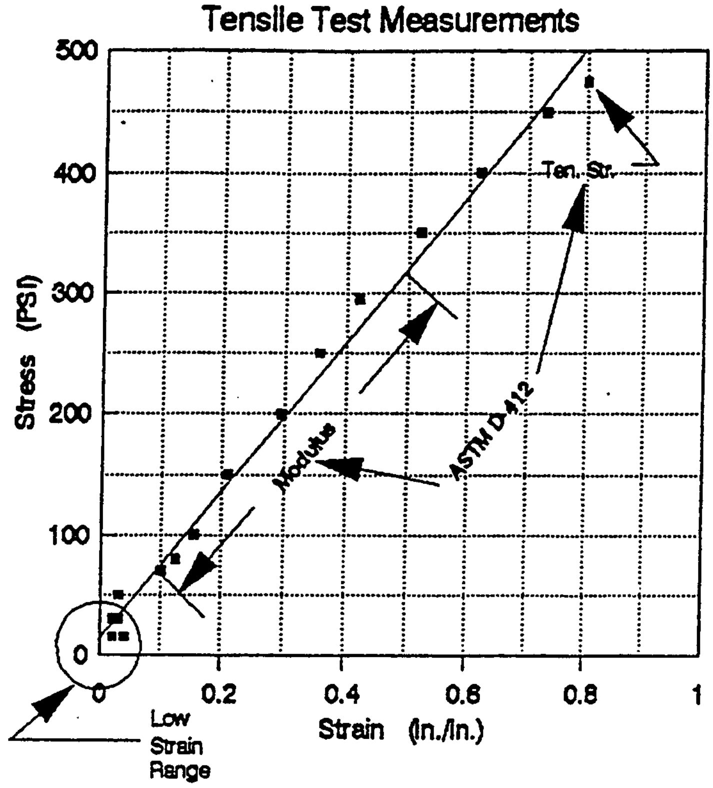


Figure 6.1-4 The Low Strain Problem

Figure 6.1-5 shows optical tensile measurements in the low strain range; Figure 6.1-6 lists Poisson's ratio measurements taken optically and Figure 6.1-7 illustrates E and u measured using a very accurate (to 5 in the third decimal place) optical measurement technique developed for this ManTech program by Dr Isaac Daniel, an experimental stress analyst at Northwestern University. This technique, the Moire' method, is described in Volume 3, Section 2.2. Table 6.1-1 compares the results of these measurements. Recall that E is the slope of the Stress/Strain curve.

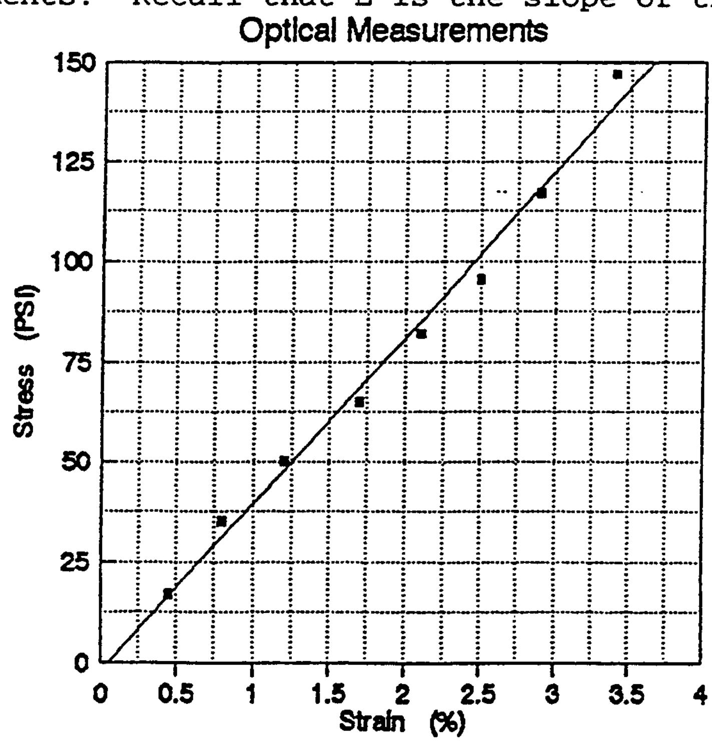


Figure 6.1-5 The Low Strain Range (0-5%)

ECCOSIL 4952N

		-40 DEG C	23 DEG C	100 DEG C
1984				
		0.50	0.46	0.46
		0.49	0.47	0.38
		0.51	0.49	0.38
	u AVG	0.50	0.47	0.41
1988		-40 DEG C	23 DEG C	100 DEG C
		0.51	0.44	0.44
		0.50	0.49	0.40
		0.56	0.44	—
	u AVG	0.52	0.46	0.42

Figure 6.1-6 Early Poisson's Ratio Measurements

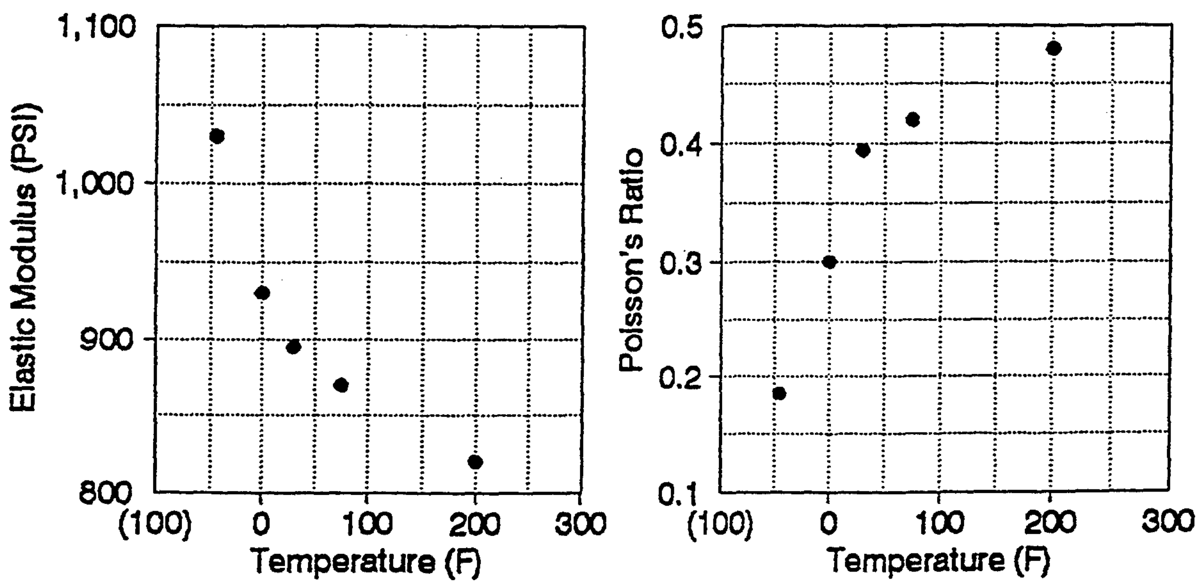


Figure 6.1-7 Tensile Measurements By Moire' Method

Table 6.1-1 Stress Measurement Comparisons

Temperature deg C	Technique	u Dimensionless	E PSI
23	ASTM D-412 (optical)	0.46-0.47	625
23	Low Strain Range		4000
23	Moire' Method	0.39-0.40	895
-40	ASTM D412 (optical)	0.50-0.52	
-40	Moire' Method	0.175-0.185	1030
+100	ASTM D-412 (optical)	0.41-0.42	
+100	Moire' Method	0.475-0.485	820

This is but one example which shows clearly that the accumulation of correct and sufficiently accurate data requires planning and investigation.

SILICONE CONSISTENCY MEASUREMENTS

Figure 6.1-8 illustrates a fundamental issue effecting consistency measurements which is peculiar to a potting material. For a potting material, all physical properties must provide required strength levels simultaneously. Whereas, for an adhesive, structural strength is the prime factor. Thus, for an adhesive, the obvious candidate for consistency determination might be shear or tensile strength of a bonded joint using the actual substrates from the application. With a potting material, however, the option is open to measure important properties indirectly and in a more cost effective and accurate manner. For example thermal conductivity and thermal expansion coefficient are typically very important potting material properties which are very sensitive to percent filler content. But, tensile, compressive and electrical properties are also sensitive to percent filler content and may be more reliable measures of consistency.

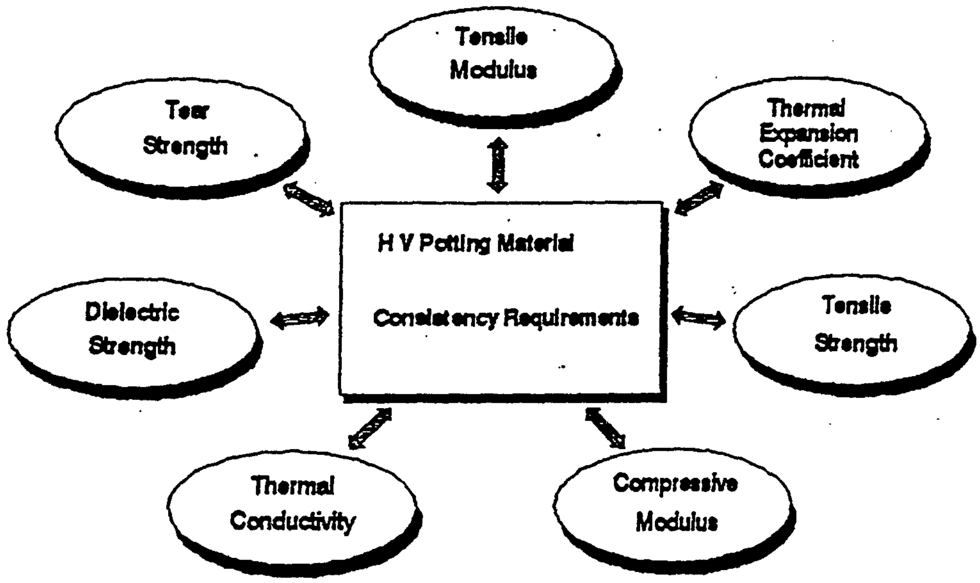


Figure 6.1-8 Interaction Of Properties

Table 6.1-2 details the extent of testing done to develop conclusions to consistency measurements of silicones. Each test was intended for each of the four materials selected for evaluation as listed in the introduction.

PARAMETER	SAMPLE SIZE	TEST SITE 1	TEST SITE 2	TEST SITE 3	NOTE NO.
Thermal Exp. Coeff.	6	Northrop Grumman	Broutman		1
Glass Trans. Temp.	6	Northrop Grumman	Broutman		2
Specific Heat	6	Northrop Grumman	Broutman		3
Tear Stren.	20	Northrop Grumman	Broutman	Grace Poly.	4
Tens. Stren.	20	Northrop Grumman	Broutman	Grace Poly.	5
Tens. Mod.	20	Northrop Grumman	Broutman		6
Comp. Mod	20	Northrop Grumman	Broutman		7
Diel. Cnst.	6	Detroit Test.	ETL Test	Hughes TSD	8
Diss. Fact.	6	Detroit Test.	ETL Test	Hughes TSD	9
Therm. Cond	6	Northrop Grumman	Hughes TSD		10
Vol. Resist.	6	Detroit Test.	ETL Test	Hughes TSD	11

Sample size chosen for 95% confidence

Room Temperature Testing Only

TEST PARAMETER DESCRIPTIONS

1) Thermal Exp.Coeff. via Thermal Mech. Analy. (TMA)

2) Glass Trans. Temp. via Thermal Mech. Analy. (TMA)

3) Specific Heat via Differential Scanning Calor. (DSC)

4) Tear Strength per ASTM D-624

5) Tensile Strength per ASTM D-412

6) Tensile Modulus per ASTM D-412

7) Compressive Modulus per ASTM D-695

8) Dielecric Constant per ASTM D-150

9) Dissipation Factor per ASTM D-150

10) Thermal Conductivity per ASTM D-177

11) Volume Resistivity per ASTM D-257

Table 6.1-2 Consistency Testing

Testing began with the tensile and compressive measurements listed in Table 6.1-2 and these early measurements effectively eliminated the SYLASTIC E and ECCOSIL 2650-5 materials. SYLASTIC E was eliminated because of high viscosity and poor de-airing properties. It was extremely difficult to make simple sheet samples for tensile tests and it was felt that that issue alone would eliminate its use as a production potting material for high voltage assemblies. Testing of ECCOSIL 2650-5 continued until it became clear that tensile and compressive properties exhibited high variations batch-to-batch. The cause for this inconsistency was traced to a high volatility constituent of the material. Figure 6.1-9 illustrates this problem.

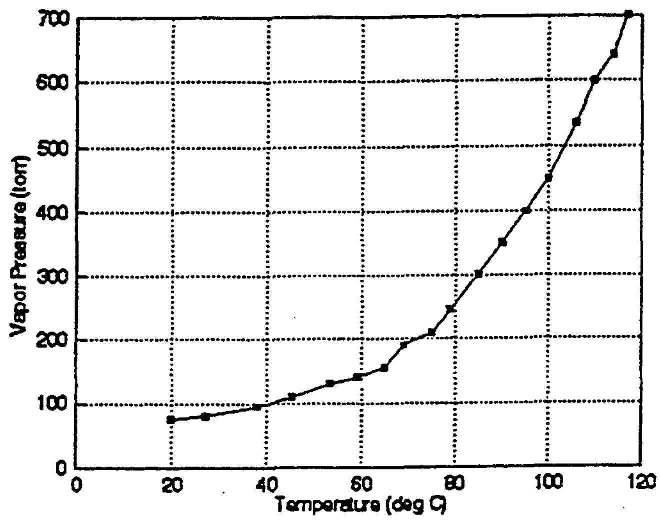


Figure 6.1-9 Vapor Pressure Curve

Mixing this heavily filled materials in production quantities caused high shear forces from the mixing blades. Temperatures to 100 degrees C were common. These temperatures caused an evaporation of the constituent to an uncontrollable extent which rendered it unacceptable for production applications.

Note in Table 6.1-2 that consistency between test sites was also monitored and proved to be an important issue. If correct and accurate measurements are required, this factor must be addressed.

Test method error also had an important impact on selecting parameters which will insure the consistent receipt of material. This is illustrated in Table 6.1-3.

Table 6.1-3 ANOVA Results

Parameter	Test Variance	Batch Variance
Tensile Modulus (PSI)	849	635
Tensile Strength (PSI)	596	330
Tear Strength (lbs/inch)	1.64	5.68
Compressive Modulus (PSI)	1550	6021

Using a standard statistical evaluation method called Analysis of Variance (ANOVA) error caused by the test method can be separated from batch-to-batch errors. The ANOVA method is illustrated in Volume 2, Section 1.2.2. Table 6.1-3 shows that test error exceeds batch error for the two tensile tests. Thus, batch consistency cannot be assured since its measurement error is swamped by test method error. The converse is true for tear strength and compressive modulus measurements, thus, making them good candidates for consistency tests.

Figure 6.1-9 summarizes the result of this consistency exercise by listing what proved to be good and bad candidates for consistency measurement and why.

	Status	Comments
TMA (CTE)	Good candidate	
TMA (Tg)	Questionable	Subject to Interp
DSC (Cp)		Subject to Interp
Tear Strength	Good Candidate	
Tensile Strength	Poor Candidate	Large Variance
Tensile Modulus	Poor Candidate	Large Variance
Compressive Modulus	Good Candidate	
Dielectric Constant	Good Candidate	
Thermal Conductivity		Expensive
Volume Resistivity	Poor Candidate	Large Variance

Figure 6.1-9 Consistency Test Conclusions

Figure 6.1-10 is a tabulation listing of approximate testing costs. These costs must be viewed, however, as first estimates. The costs shown were quoted in advance based on previous work but not necessarily representative of the tests shown in Table 6.1-3. No attempt was made to re-estimate new prices based on the actual work done. However, the relative comparisons are interesting.

	SAMPLE SIZE	NORTHROP ESD	BROUTMAN	EMERSON & CUMING	DETROIT TEST LABS	ELECTRICAL TEST LABS	HUGHES TSD
TMA (CTE)	6	146	250				
TMA (Tg)	6	146	101				
DSC (Cp)	6	438	101				
TEAR STR	20	14	15	n/c			
TENSILE STR	20	21	75	n/c			
TENSILE MOD	20						
COMPRESSIVE MOD	20	53	105				
DIELECTRIC CONST	6				47	38	70
THERMAL COND	6	366					263
VOLUME RESIST	6				47	38	83

Figure 6.1-10 Testing Costs (per sample)

SILICONE CHARACTERIZATION

The stress modeling flow chart shown in Figure 6.1-11 serves to illustrate a prime requirement of material characterization, i.e. input values to engineering stress modeling exercises. Thermal, structural, and electrostatic models all demand that the effects of temperature dependence be accounted for in an accurate analysis. An equally important requirement is that the temperature dependent parameters must be established to serve as a baseline for future exercises to improve a product or to replace a material. Without a basis for comparison with a "known good", material, future changes can lead to problems.

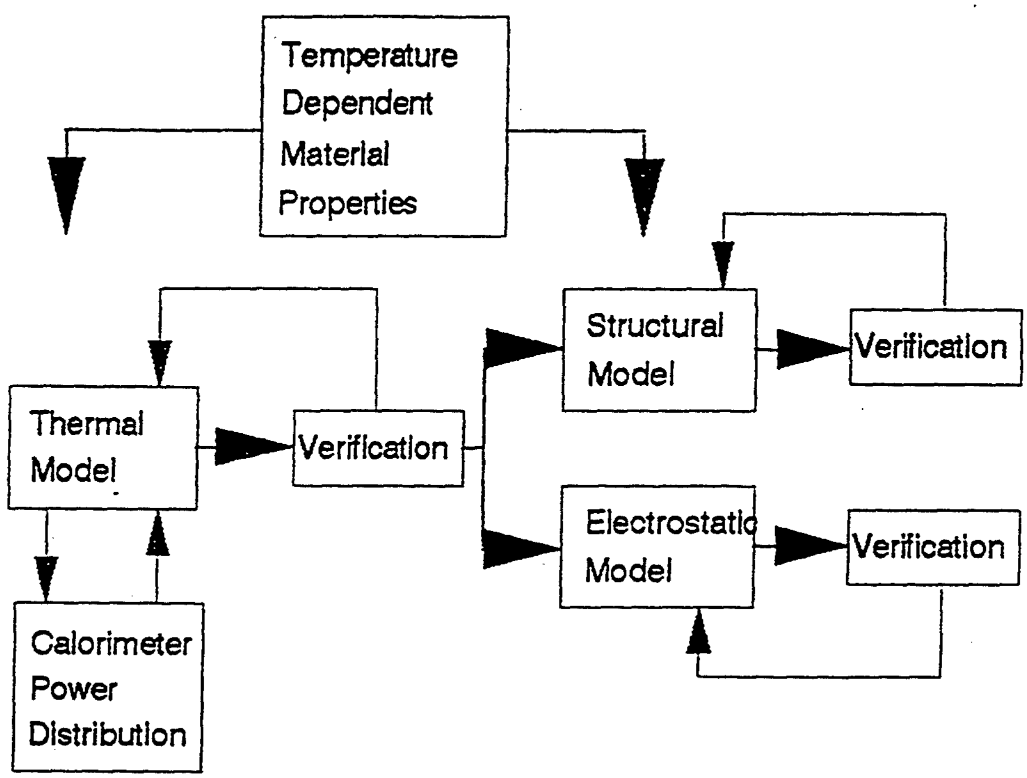


Figure 6.1-11 Stress Modeling Flow Chart

Only one test site was used per characteristic measurement. The selection was based somewhat on the consistency measurement program which lead to either more reliable or more cost effective measurements plus, of course, the capability to introduce temperature dependance. The test measurement temperatures were limited to only three values (-55C, +25C, +100C) because of cost constraints.

Listed below are the results of this exercise.

Compressive Modulus (psi)

Material	Temperature (°C) -55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 1369 St. Dv. = 134 n (Samp) = 24 COEVAR = 9.8%	Mean = 892 St. Dv. = 44 n (Samp) = 24 COEVAR = 4.9%	Mean = 1090 St. Dv. = 67 n (Samp) = 24 COEVAR = 6.2%
Silicone Unfilled RTV-615 (GE)	Mean = 505 St. Dv. = 19 n (Samp) = 24 CoEVar = 3.8%	Mean = 5389 St. Dv. = 31 n (Samp) = 23 CoEVar = 0.6%	Mean = 556 St. Dv. = 28 n (Samp) = 24 CoEVar = 5.0%

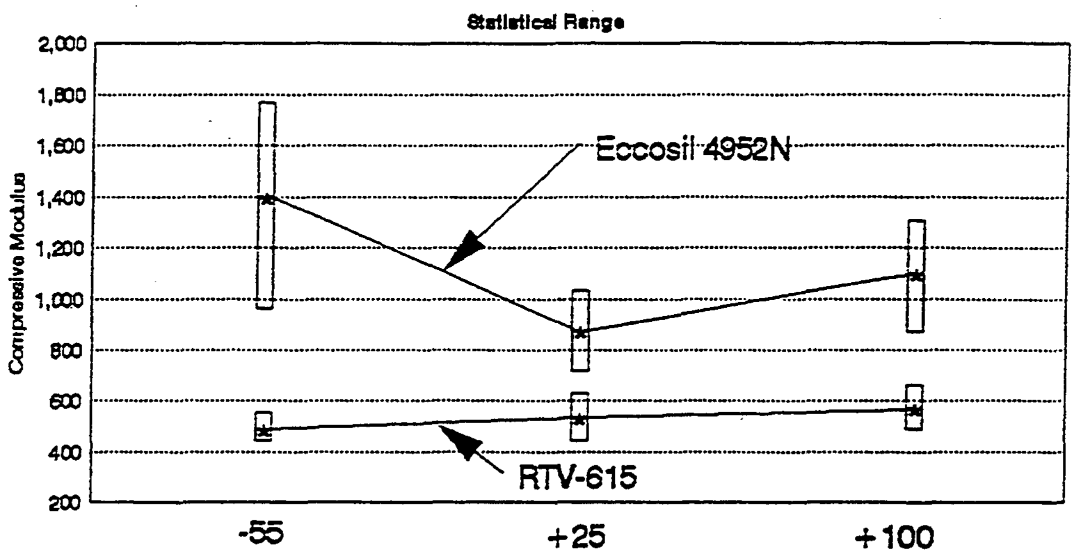


Figure 6.1-13 Statistical Range At Three Temperatures

Note from Figure 6.1-13 showing the compressive modulus data plotted as bars representing the mean values +/- three standard deviations that there is overlap of values at the three test temperatures. In this particular case, with a test sample size of 24 and standard deviations of less than ten percent of the mean values, this spread of data can be treated with high confidence. Any stress analyses of these materials should include a sensitivity study which addressed the data spread. The coefficient of variation (CoEVar) is a measure of variability that is "free" of the location of the data or adjusts for location or conditions of the data taking. It is a ratio defined as

$$\frac{\text{Std Dev}}{\text{Mean}} \times 100$$

and is helpful to quantify the standard deviation when the averages are substantially different from each other.

Plots of the statistical spread of data for the following parameters is left to the reader.

Compressive Strength (psi)

	Temperature (°C)		
Material	-55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 790 St. Dv. = 75 n (Samp) = 24 CoEVar = 9.5%	Mean = 562 St. Dv. = 36 n (Samp) = 24 CoEVar = 6.4%	Mean = 526 St. Dv. = 28 n (Samp) = 23 CoEVar = 5.3%
Silicone Unfilled RTV-615 (GE)	Mean = 219 St. Dv. = 26 n (Samp) = 24 CoEVar = 12%	Mean = 215 St. Dv. = 11 n (Samp) = 23 CoEVar = 5.1%	Mean = 210 St. Dv. = 7 n (Samp) = 24 CoEVar = 3.3%

Dielectric Constant

Temperature (°C)

Material	-55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 2.9 St. Dv.= .03 n (Samp) =12	Mean = 2.9 St. Dv.= .03 n (Samp) =12	Mean = 2.8 St. Dv.= .02 n (Samp) =12

Dielectric Strength (volts per mil)

Temperature (°C)

Material	-55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 318 St. Dv. = 26 n (Samp) = 10	Mean = 326 St. Dv. = 20 n (Samp) = 10	Mean = 390 St. Dv. = 33 n (Samp) = 10

Tear Strength (ppi)

Temperature (°C)

Material	-55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 41 St. Dv. = 2.9 n (Samp) = 20	Mean = 28 St. Dv. = 1.3 n (Samp) = 20	Mean = 25 St.Dv. = 2.4 n (Samp) = 20

Tensile Strength

Temperature (°C)

Material	-55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean = 1053 St. Dv. = 194 n (Samp) = 40	Mean = 610 St. Dv. = 19 n (Samp) = 40	Mean = 456 St. Dv. = 27 n (Samp) = 40
Silicone Unfilled RTV-615 (GE)	Mean = 992 St. Dv. = 104 n (Samp) = 40	Mean = 719 St. Dv. = 84 n (Samp) = 40	Mean = 480 St. Dv. = 108 n (Samp) = 40

Volume resistivity (ohm-cm)

Material	Temperature (°C) -55	+25	+100
Silicone Heavily Filled Eccosil 4952N (Grace)	Mean= 1.4E+14 StDv= 2.4E+13 n (Samp) = 10	Mean= 5.5E+13 StDv= 9.5E+12 n (Samp) = 10	Mean= 9.4E+12 StDv= 3.0E+12 n (Samp) = 10

SILICONE DOCK-TO-STOCK PROGRAM

This effort was not a task of the original material testing flow chart shown in Figure 6.1-1 but rather an outgrowth of it. The four year time span covered by this silicone material program saw a pronounced evolution in the relationship between NG-ESD the user/contractor and Grace Specialty Polymers the formulator/supplier of ECCOSIL 4952N. Initially Grace was not interested in getting into the test business and NG-ESD was reluctant to trust supplier data. This was a clear example of the adversarial relation which typically existed between supplier and user. The supplier, frequently not knowing what a product was being used for, would conduct an acceptance inspection of their raw materials but provide very little information concerning the finished product. The user was only interested in the attributes of the final product and was ,therefore, required to do extensive acceptance testing across a broad range of products. If user data showed parameters to be "out of range" liability for this condition was frequently unresolved and corrective action was poorly defined.

Economic conditions across all industries in the past few years influenced this condition greatly. Cost cutting measures prompted users to ask suppliers to provide better data and control on their product and users had to accept the fact that an extensive material testing capability was costly and that an acceptance of more efficiently collected supplier data had to become the norm. Consequently NG-ESD and Grace agreed to develop a process which would lead to a Dock-To-Stock acquisition of ECCOSIL 4952N. In turn, this exercise would serve as a basis for similar agreements across all product lines.

A Dock-To-Stock procedure is exactly that, i.e. the supplier does the acceptance testing to mutually agreed upon specifications and the user accepts the supplier data and moves the product directly into stock without further acceptance testing. Obviously trust is required between all parties. The ECCOSIL 4952N silicone material used for this exercise is a heavily filled condensation cured material used extensively by NG-ESD for high voltage packaging.
The two main tasks required to initiate a Dock-To-Stock agreement are:

Revise specifications This process involves 1), selecting test parameters and test methods which best describe the material 2), a confirmation of test consistency by conducting a round robin comparison test between supplier and user and 3), acceptance by both parties.

Develop Statistical Process Controls (SPC) This process establishes acceptance and processing parameters for long term process control. It generally follows classically defined methods for establishing SPC requirements, however, the requirements for early production batches may require special agreement. Again, acceptance by both parties is necessary.

The specification revision rational used in this case for ECCOSIL 4952N involved the following items.

A robust application This material had been in use by NG-ESD for some years as a high voltage packaging material and no correlation had ever been established between material properties and equipment performance, i.e. the material "Worked".

Base acceptance criteria on consistency data High confidence and control limits had already been established.

Base qualification criteria on characterization data Again, high confidence with appropriate limits had already been established.

Write the specification per the format and content of MIL-STD-490A

The specification kickoff meeting was treated very seriously and included four representatives from Grace Specialty Polymers, two people from NG-ESD engineering, three people from NG-ESD manufacturing, one person from NG-ESD purchasing and a consulting statistician.

Based on the consistency testing program tear strength and compressive modulus were selected as acceptance parameters which best described the product in an accurate and cost effective manner as described in the consistency section of this report.

The graphic in Figure 6.1-14 is an intuitive representation of the four typical states of a process and show the relationships which exist between specification limits and control limits. The goal, of course, is to remain in the ideal state. The chaos state requires a work stoppage and the two in-between states require some type of corrective action.

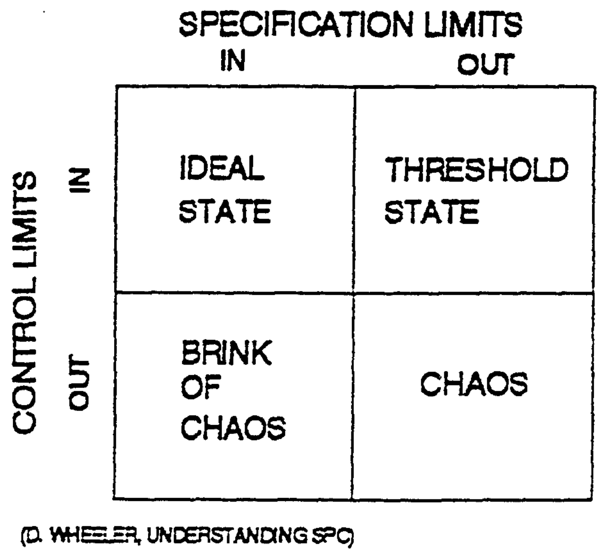


Figure 6.1-14 Four states Of A Process

The normal establishment of SPC limits requires data from 20 lots of material. Since the material in question had produced data to this extent it formed the basis for the first control charts. However, since it could take months and perhaps years to acquire this data for a new material a preliminary agreement for future SPC exercises established that specification limits be re-established after every five batches of material accepted for a program. It is recognized that there may be additional supplier and user risk attached to such a procedure, however, a mutually cooperative effort should be able to quell major disturbances. Figure 6.1-15 shows the specification changes which would have evolved with ECCOSIL 4952N over four sets of five material batches. The mean of tear strength and both upper specification limit (USL) and lower specification limit (LSL) changed with subsequent re-evaluations. It is obvious from Figure 6.1-14 that material accepted based on 21 batches of material could have failed the acceptance criteria established after only five batches.

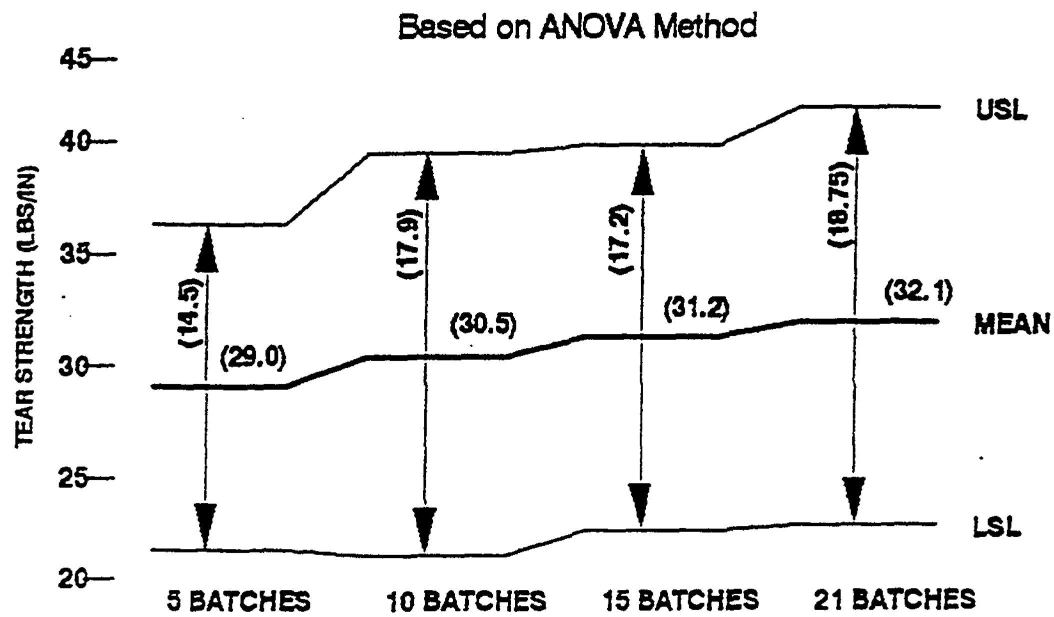


Figure 6.1-15 Eccosil 4952N Specification Changes

Figure 6.1-16 examines the result of one round robin test comparison of tear strength using samples prepared only by NG-ESD but tested by both Broutman Associates and Grace. Recall that Broutman Associates is an independent mechanical testing laboratory. Both sets of data were within the USL and LSL. Using a linear multiplication factor of 1.31 on the Grace data the two curves become almost coincident. This is an example of data which is consistently inconsistent.

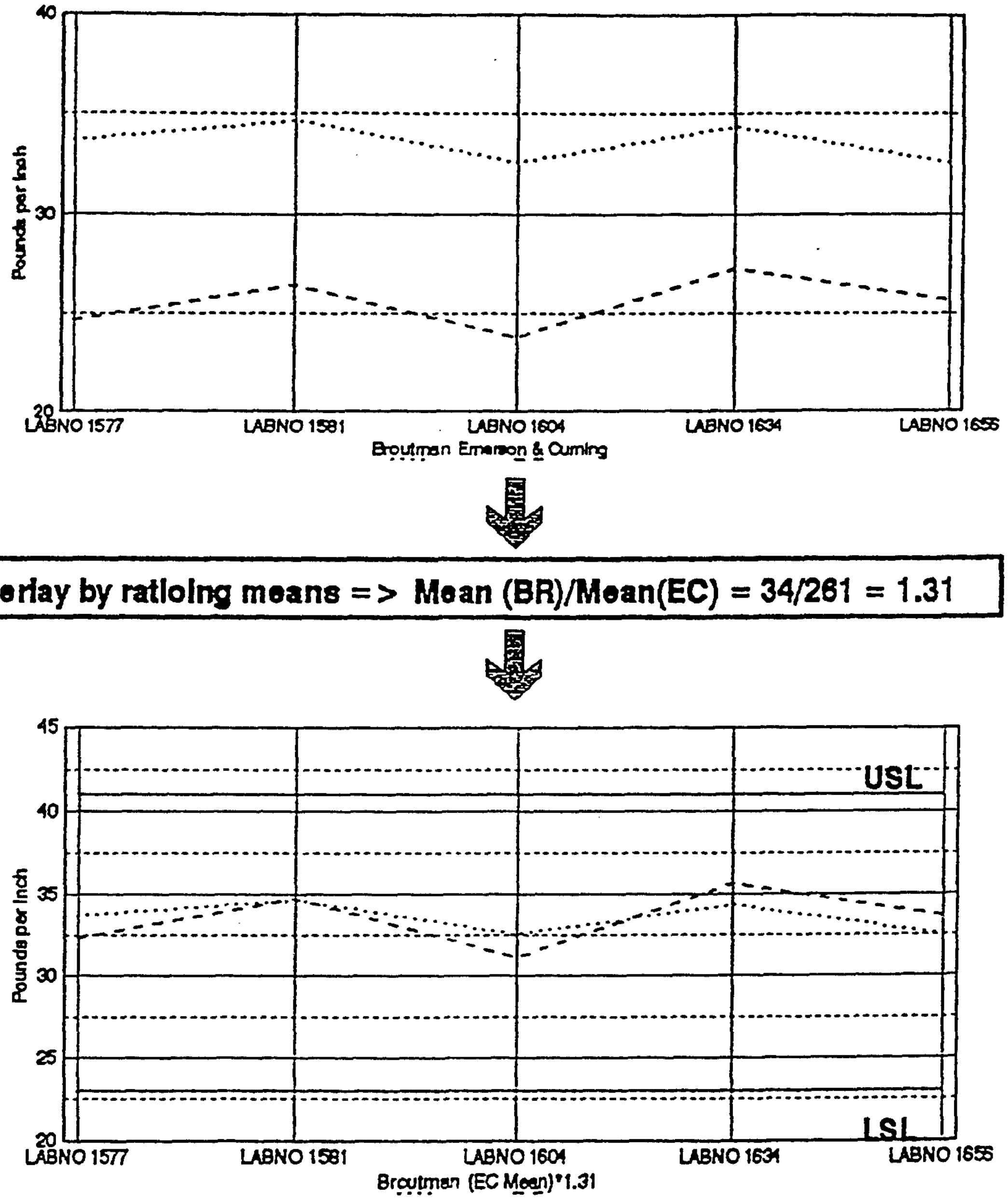


Figure 6.1-16 Results Of Round Robin Tear Strength Tests

Figure 6.1-17 is another interesting result of a round robin test between NG-ESD and Grace. In this case again, NG-ESD prepared all of the samples but used two different cure schedules with one being the normal NG-ESD cure and the other being a recommended Grace cure. Both NG-ESD and Grace tested samples of both cure schedules. Comparing the results of these four groups of data to the previously established specification acceptance limits shown as the range on the far right of the illustration put all four group within the specification limits - an ideal situation. The resulting Dock-To-Stock agreement was based on these two round robin test sequences. The revised specification which governs this agreement is included in Volume 3, Section 2.8, Potting compound material specification guidelines are included in Volume 3, Section 2.7.

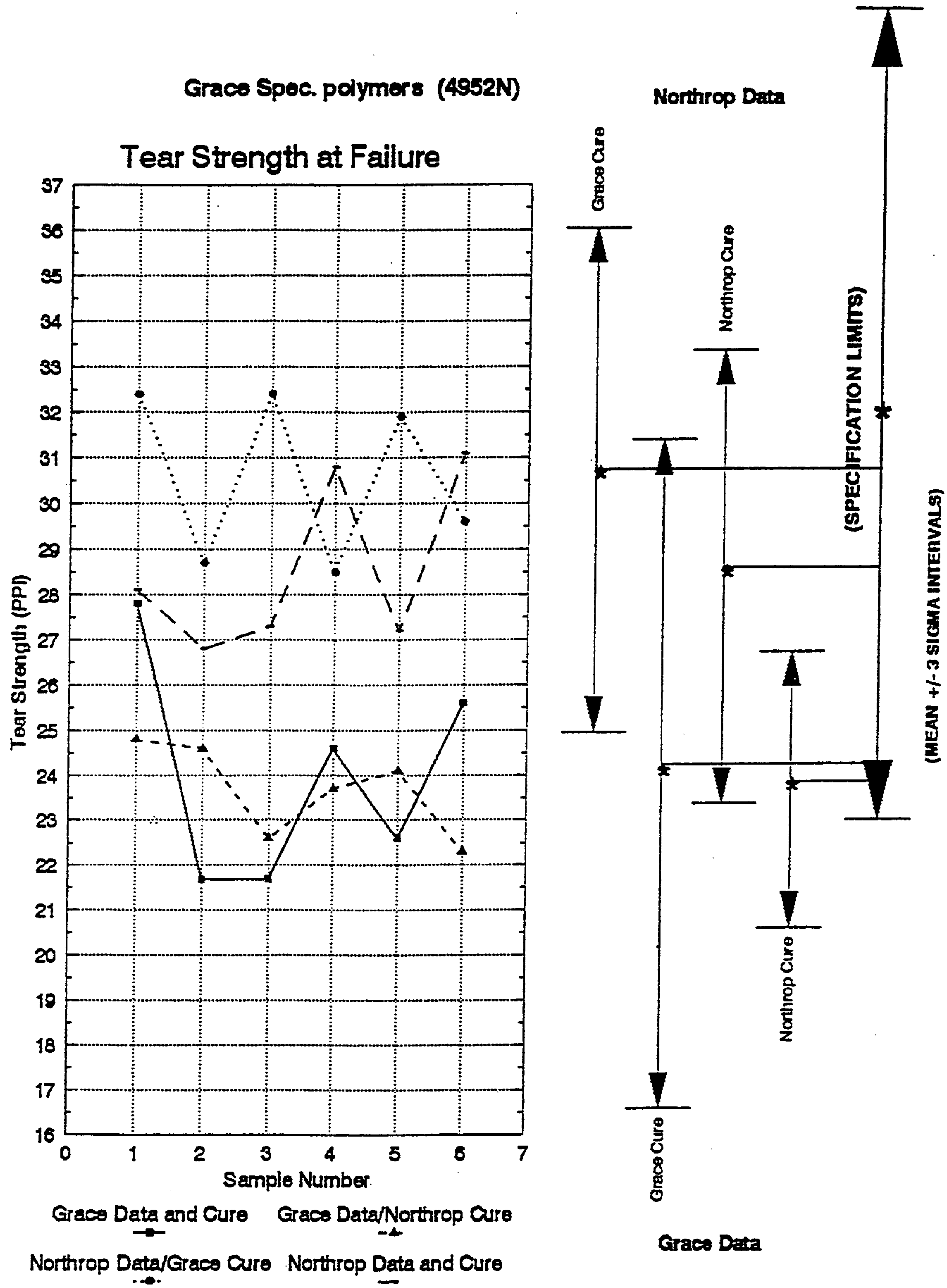


Figure 6.1-17 Round Robin Exercise

Traditional Shrewhart control charts for Compressive Modulus and Tear Strength were also developed from the 21 batches of material property measurements. Because the Shrewhart control limits assume a constant subgroup size (ie., batch size), the first five batches were omitted prior to calculating the control limits. For Tear Strength and Compressive Modulus, three control charts were recommended by the NGESID statistical process control group to provide good control over the receipt of material. Using Tear Strength as an example, Figures 6.1-18, 6.1-19 and 6.1-20 depict these three types of control charts, average (XBAR) tear strength, within batch standard deviation (s), and between batch moving range (MR). The average control chart was chosen as a monitoring tool to show the supplier via batch to batch information how well the product is being produced. The within batch standard deviation control chart provides the supplier with information as to how consistent was the batch of test specimens. The third control chart essentially monitors batch to batch consistency between the average tear strengths. Thus , all three control charts serve a separate but collective purpose to measure the quality of the silicone as seen through Tear Strength.

Because the quality of the silicone is being determined by destructive testing metrics, the fabrication of test specimens becomes an extremely important process in itself. Control and consistency of the specimen fabrication process must be carefully monitored. Any indication of inconsistency will make the average control chart misleading. Guidelines for sample preparation can be found in Volume 3, Section 2.3.
Note from Figure 6.1-18, the average Tear Strength for batches 16 and 18 were statistically high compared to the others. In the case of high Tear Strength, these two batches show glimpses of improvement (based on the higher the Tear Strength the better the quality of Silicone). On the other hand, Figure 6.1-19 depicts out of control conditions for batches 14, 17, and 19. This indicates significantly more variability occurring in the testing/specimen fabrication process. These are clear signals that investigation should be undertaken to improve the test vehicle processes. Conversely, Figure 6.1-20 shows consistency in the average Tear Strength between batches. This key chart provides a clear measure of assurance of the quality of the Silicone for the Tear Strength attribute.

The above traditional control charting methods can be applied easily given "enough" subgroups (ie., batches) as provided by this program. However, a typical production supply may involve far fewer batches of material delivered in a short period of time and therefore the above control charts would require substantial data collection over many years. In order to mitigate this situation and establish effective control charts immediately, a "Short Run" philosophy was initiated*.

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* D. Bothe, Short Run Control Charts, U.S. Army DAAA08-88-M-7649

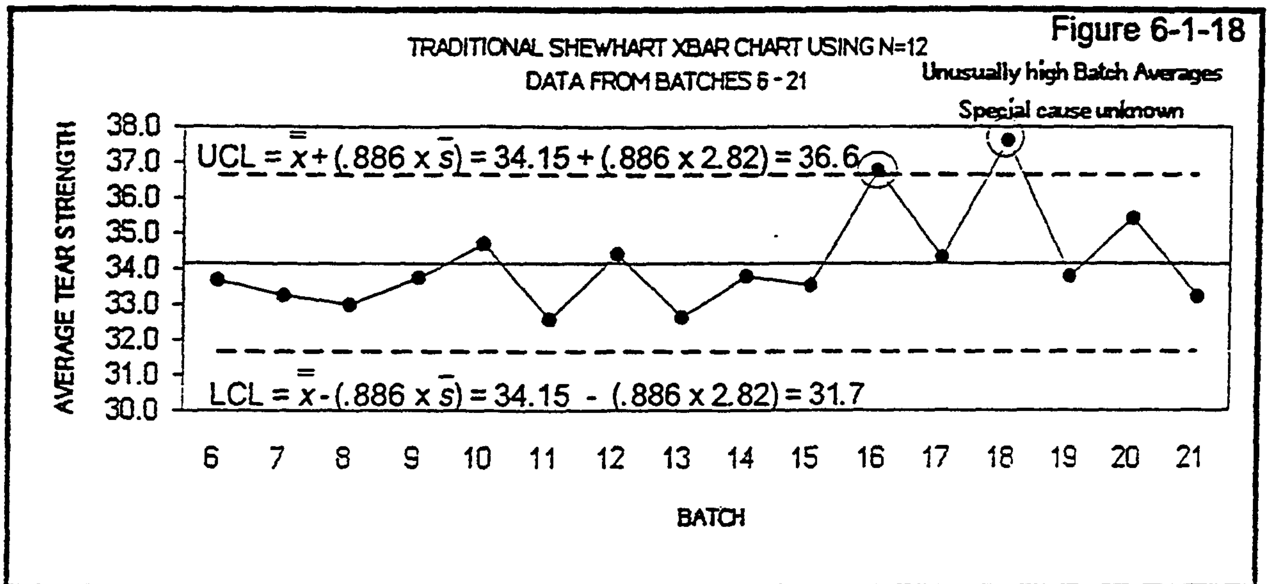


Figure 6-1-18

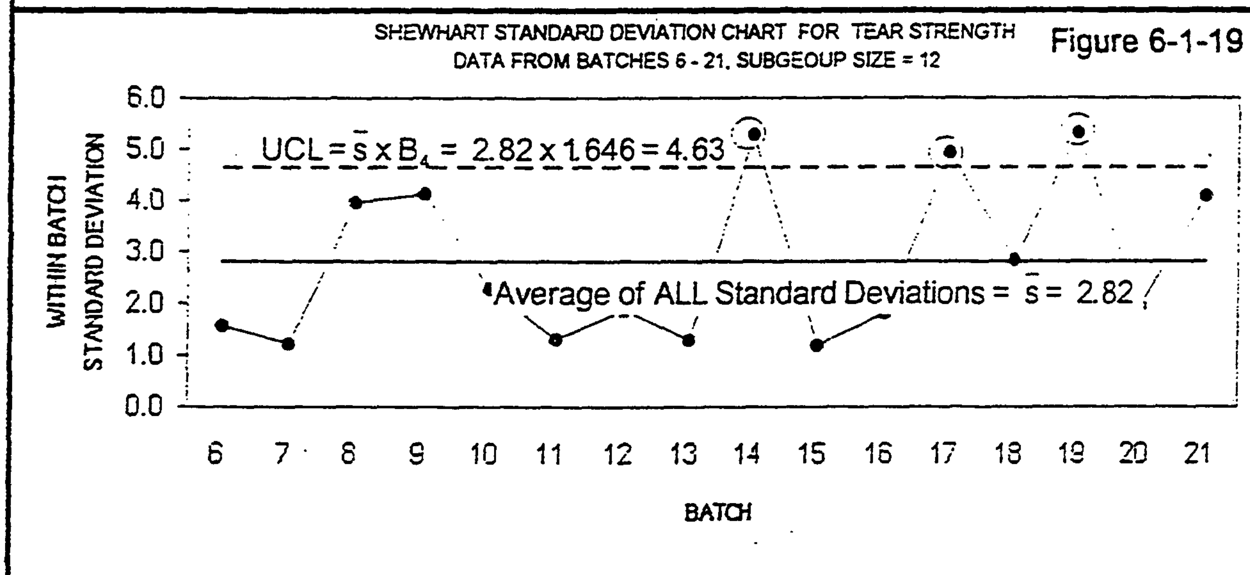


Figure 6-1-19

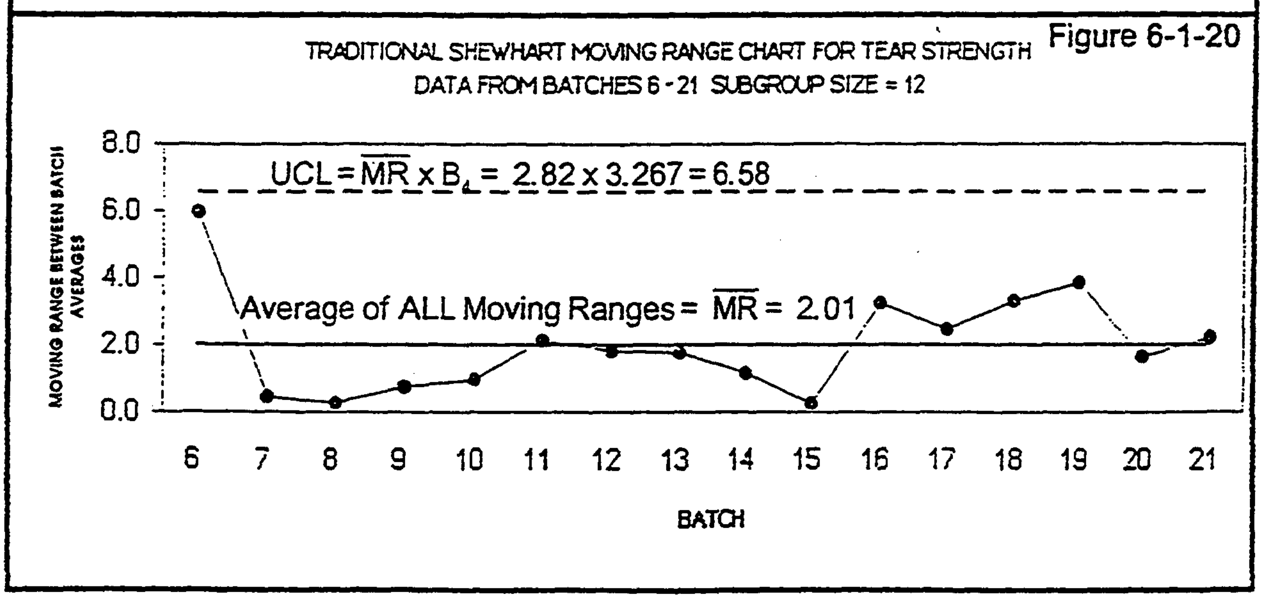


Figure 6-1-20

These Short Run control charts are essentially the same as the traditional control charts; they have control limits and a plotted characteristic over time. Where they differ is in their plotted points. For example, using the short run XBAR chart of figure 6.1-21, the plotted point is no longer the average of 12 Tear Strengths (batch average), but the point is now:

$$\frac{\text{Batch Average - Historical Average}}{\text{Historical Average Of Batch Standard Deviations}}$$

and the control limits become the statistical constant used in the traditional Shrewhart chart, namely +/- 0.866. Referring to figure 6.1-22 and 6.1-23, the short run complements of the traditional Shrewhart charts can be seen. The advantage of these Short Run charts is their ability to apply and use the statistical control limits on the FIRST batch of data. This is very advantageous when seeking process improvements.

For those who wish to focus on Silicones, the following is a cross reference guide to specific program details, procedural details and reference information in Volumes 2, 3 and 4 respectively that relate specifically to that subject:

Volume 2 Program Details

Section 1.2.2 Analysis of variance (ANOVA)
This section contains a tutorial on ANOVA which is a method for statistically comparing the relationship of several groups of data. The section also includes a paper by Dr. Tamhane of Northwestern University applying ANOVA to silicone testing and relating its application to calculate control limits.

Section 1.2.3 Statistical Test Plan for Characterizing Materials and Components
This section provides guidelines to establish a statistical test plan including sample size, success criteria and desired level of confidence.

Section 2.0 Characteristics of Encapsulants
The section discusses the desirable characteristics of encapsulants and their related attributes. Several encapsulant material classes are qualitatively evaluated against the more common encapsulant parameters. Standard test methods are listed for encapsulant properties.

Section 5.0 Cost-Benefit Analysis
This section provides guidance in determining sample size for material and component testing to insure meaningful results.

Volume 3 Procedural Details

Section 2.1 Designing a Significant Experiment
This section provides a methodology for designing a statistically significant experiment including determining sample size, randomization and analysis of data.

Section 2.2 Mechanical Characterization of Silicone Rubber
A method is provided for making precise measurements of Elastic Modulus and Poisson's ratio for elastomeric materials operating in the low strain range.

Section 2.3 Sample Preparation
The methodology used to prepare test samples of Eccosil 4952N is provided.

Section 2.4 Test Method for Tensile Properties
This section provides the test procedure used to measure the tensile strength of encapsulant materials.

Section 2.5 Test Methods for Tear Strength
This section provides the test procedures for measuring the tear strength of encapsulant materials.

Section 2.6 Detroit Testing Lab Report
Detroit Testing Laboratory was funded to conduct volume resistivity and dielectric constant measurements of Eccosil 4952N encapsulant material.

Section 2.7 Material Specification Guidelines
This section provides recommendations and guidelines for preparing a detailed encapsulant material specification.

Section 2.8 Material Specification
This is the specification used by Northrop Grumman for Eccosil 4952N. It is the basis for the Dock-To-Stock agreement with Emerson and Cuming (Grace Specialty Products).

Volume 4 Reference Information

Section 1.3 Silicone Rubber Test Structures
This section provides the method used to make the test structures for tensile and tear strength testing.

Section 1.4 Encapsulated Electrode Pair Model Test Structure
The test structure used used to evaluate corona and electrical breakdown characteristics of various encapsulants is provided.

Section 2.1 Corona and Breakdown Performance of Specific Materials
This section provides the results of corona and breakdown performance testing for specific materials using the model test structure described in Section 1.4.

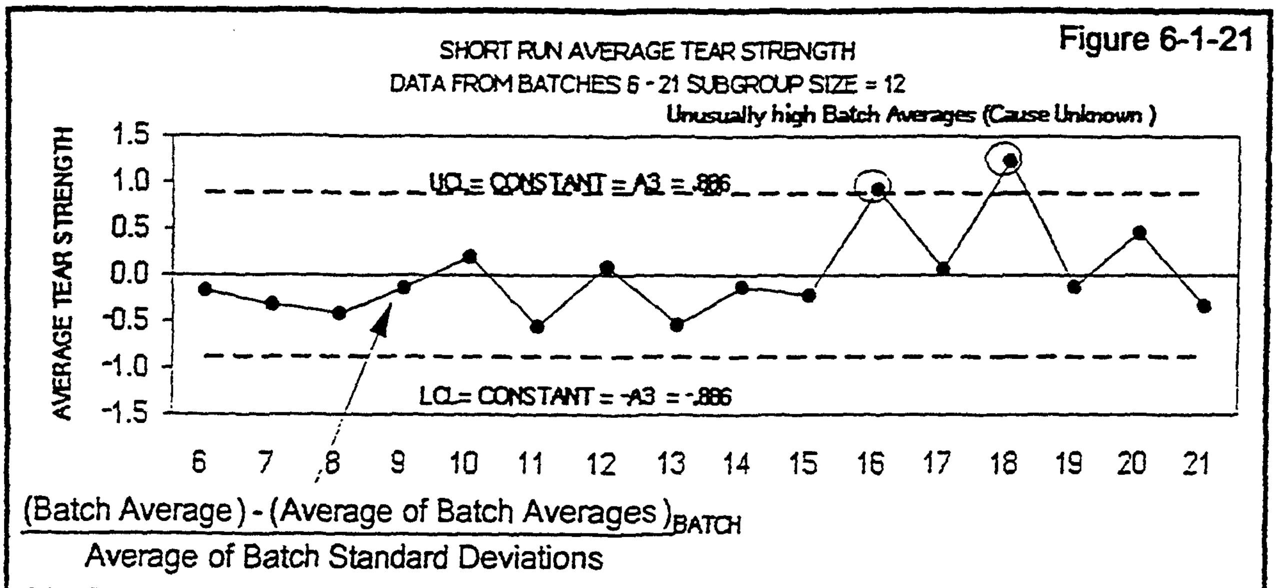


Figure 6-1-21
SHORT RUN AVERAGE TEAR STRENGTH
DATA FROM BATCHES 6 - 21 SUBGROUP SIZE = 12
Unusually high Batch Averages (Cause Unknown)
AVERAGE TEAR STRENGTH
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
UCL = CONSTANT = A3 = .886
LCL = CONSTANT = -A3 = -.886
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
(Batch Average) - (Average of Batch Averages)BATCH
Average of Batch Standard Deviations

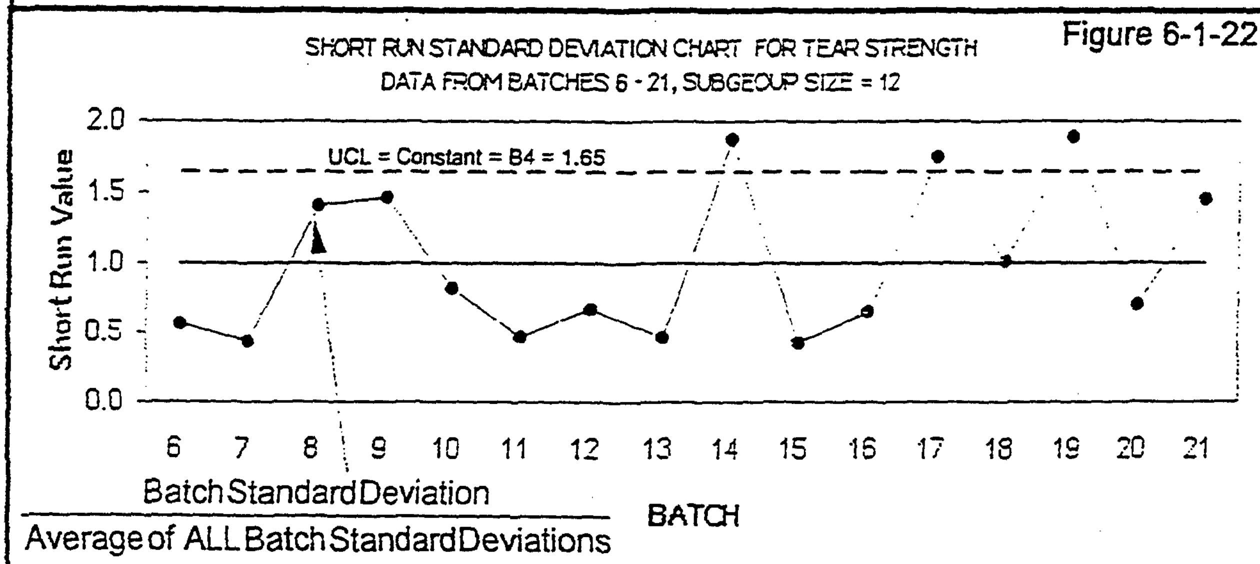


Figure 6-1-22
SHORT RUN STANDARD DEVIATION CHART FOR TEAR STRENGTH
DATA FROM BATCHES 6 - 21, SUBGROUP SIZE = 12
Short Run Value
2.0
1.5
1.0
0.5
0.0
UCL = Constant = B4 = 1.65
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
Batch Standard Deviation
Average of ALL Batch Standard Deviations
BATCH

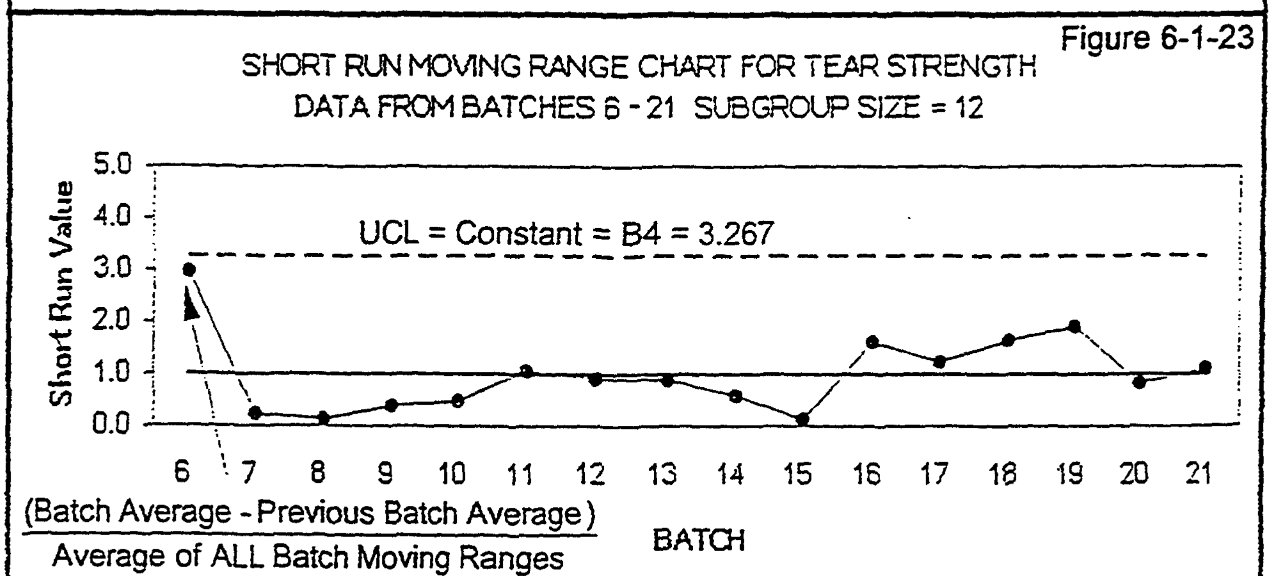


Figure 6-1-23
SHORT RUN MOVING RANGE CHART FOR TEAR STRENGTH
DATA FROM BATCHES 6 - 21 SUBGROUP SIZE = 12
Short Run Value
5.0
4.0
3.0
2.0
1.0
0.0
UCL = Constant = B4 = 3.267
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
(Batch Average - Previous Batch Average)
Average of ALL Batch Moving Ranges
BATCH

6.1.2 Epoxies

6.1.2.1 Characterization

During our characterization studies, the physical, chemical, thermal, and electrical properties of seventeen different epoxy encapsulant material candidates were studied. The purpose of these studies was not to identify the one best material for all possible encapsulation applications, an impossible task, or even the one best material for a single encapsulation application, a task of limited value to others. Rather, the purpose of these studies was to assemble a self-consistent set of data on materials properties that are important and relevant to HVPS encapsulation, all of which were obtained using well-documented, standard tests. Armed with this data, other workers in the field could select an encapsulant, from those in our study, that is appropriate for their application. Alternatively, using the same test methods, they could perform tests on a range of other encapsulant candidates, and compare their results to those in our data tables.

A total of 17 materials were chosen for characterization. Epon 825/HV and Scotchcast 280 were selected as the baseline because of Hughes' long and favorable experience with them as HV encapsulants. The remaining materials were identified in previous surveys as materials commonly used for high voltage applications. The materials selected are shown in Figure 6.1-4; the testing methodology and test results are provided in Volume 4 Section 2.6.

It is strongly recommended that workers considering the use of new materials as HVPS encapsulants subject them to a battery of tests, relevant for their specific application, using the tiered test methodology and the test methods outlined in Volume 4 Section 2.6. In this way, the performance of these new materials can be compared to the previously tested encapsulants. Materials selection can then be done using the Quality Function Deployment (QFD) form for encapsulant materials that appears in Appendix 1-1 of Volume 2 of the guidelines, supplemented by the data collected on the new materials, as well as the tabulated data appearing in Volume 4 Section 2.6. As always, the conclusions drawn from the QFD analysis should be subjected to critical analysis by the entire multi-functional concurrent engineering team.

Figure 6.1-5 Status - Cure Completion Program

(STYCAST 2651MM)

TEST	SMPL SIZE	8% Catalyst CURE 1	8% Catalyst CURE 2	8% Catalyst CURE 3	7% Catalyst CURE 1	7% Catalyst CURE 2	7% Catalyst CURE 3	COMMENTS
FT-IR SPECTROSCOPY	6	C/C	C/C	C/C	C/C	C/C	C/C	Data collected at six hour intervals
EQUILIBRIUM SWELLING	6	C/E	C/E	C/E	E	E	E	Extensive Development Required
Tg (via DSC)	6	C/C	C/C	C/C	C/C	C/C	C/C	Data collected at six hour intervals
CURE HEAT (via DSC)	6	/C	/C	/C	/C	/C	/C	Data collected at six hour intervals
WEIGHT LOSS (via TGA)	6	*/C						* Alternate Cure
VOLUME RESISTIVITY	6	/C	E	E	E	E	E	Impractically Long Test Time

CURE 1, 5 HRS @ 80 C PLUS 12 HRS @ 100 C PLUS 8 HRS @ 120 C (Northrop Cure)
CURE 2, 12 HRS @ 120 C (Under Cured)
CURE 3, 15 HRS @ 150 C (Over cured)

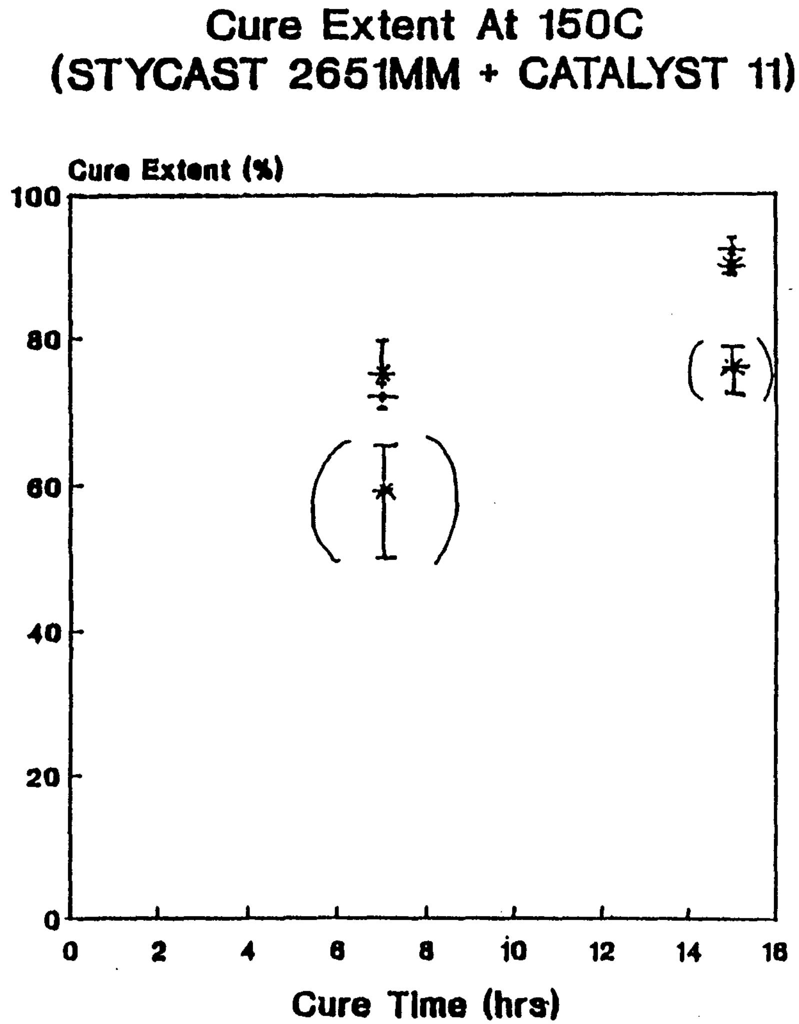
* Alternate Cure, 8 HRS @ 100 C PLUS 12 HRS @ 120 C PLUS 15 HRS @ 150 C

C => Test Completed
P => Test In Progress
S => Samples In Preparation
E => Ended-Too Costly

NU/NOR

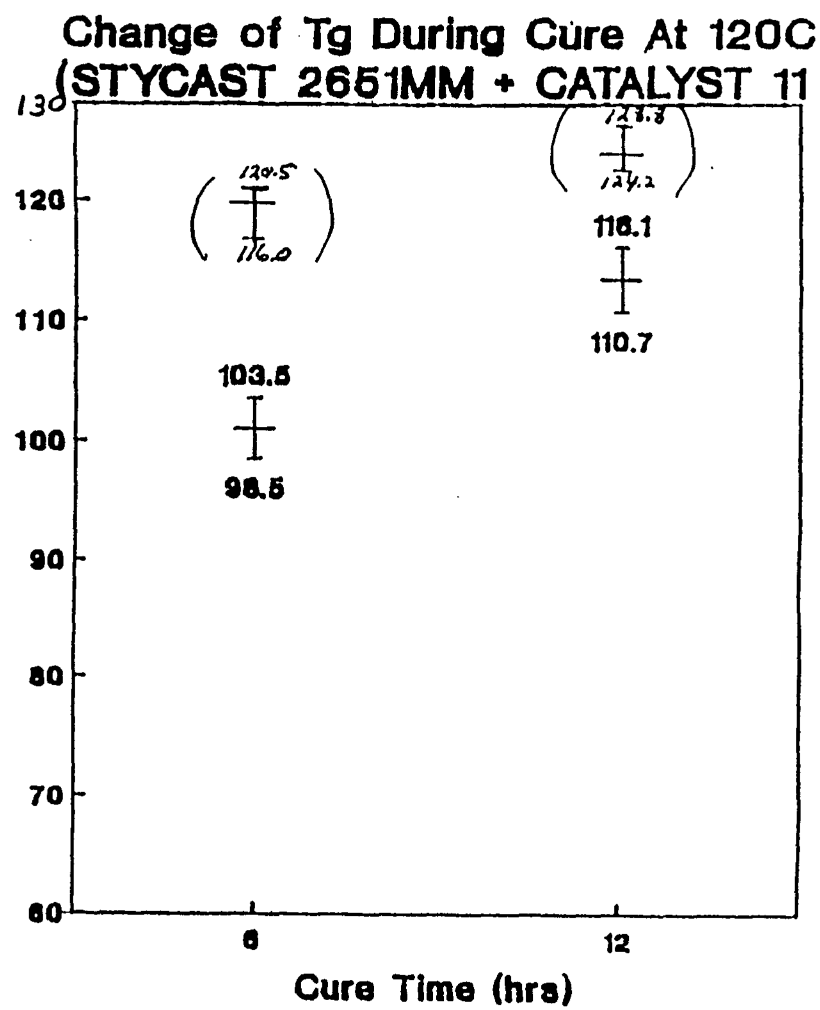
Figure 6.1-6 Status - Cure Completeness Comparisons

6.1-6a FTIR Cure Extent



Cure schedule 2: 15hrs at 150C.
Measured by Mattson FTIR.
Measured by Nicolet FTIR, ( )

6.1-6b DSC Cure Extent



Cure schedule 2: 12hrs at 120C.
8% hardener.
Measured by Perkin-Elmer DSC 7.
Measured by TA Instruments System 9900 ( )

Note from Figure 6.1-5 that efforts to monitor extent of cure via changes in volume resistivity and solvent swelling were dropped as being overly time consuming. in the case of volume resistivity, it simply took to long (several hours) for readings to stabilize. The solvent swelling program was always understood to be highly theoretical in nature, but of enough utility to warrant inclusion in the MANTECH program. This may still be true but it became obvious that too much additional work would be required to reach conclusions that could be considered useful in a manufacturing environment.

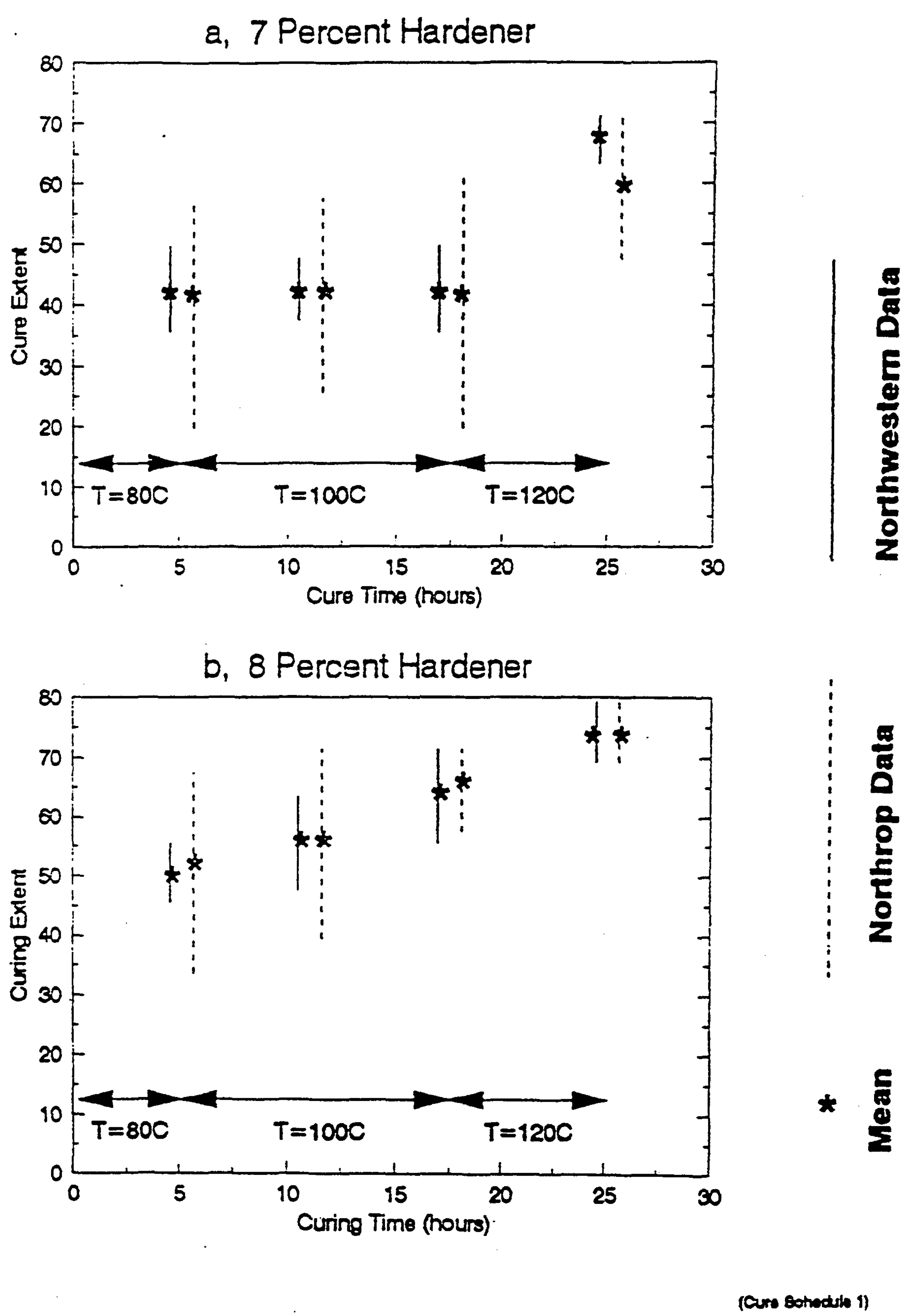


Figure 6.1-7 **Curing Extent via FTIR (95% confidence intervals)**

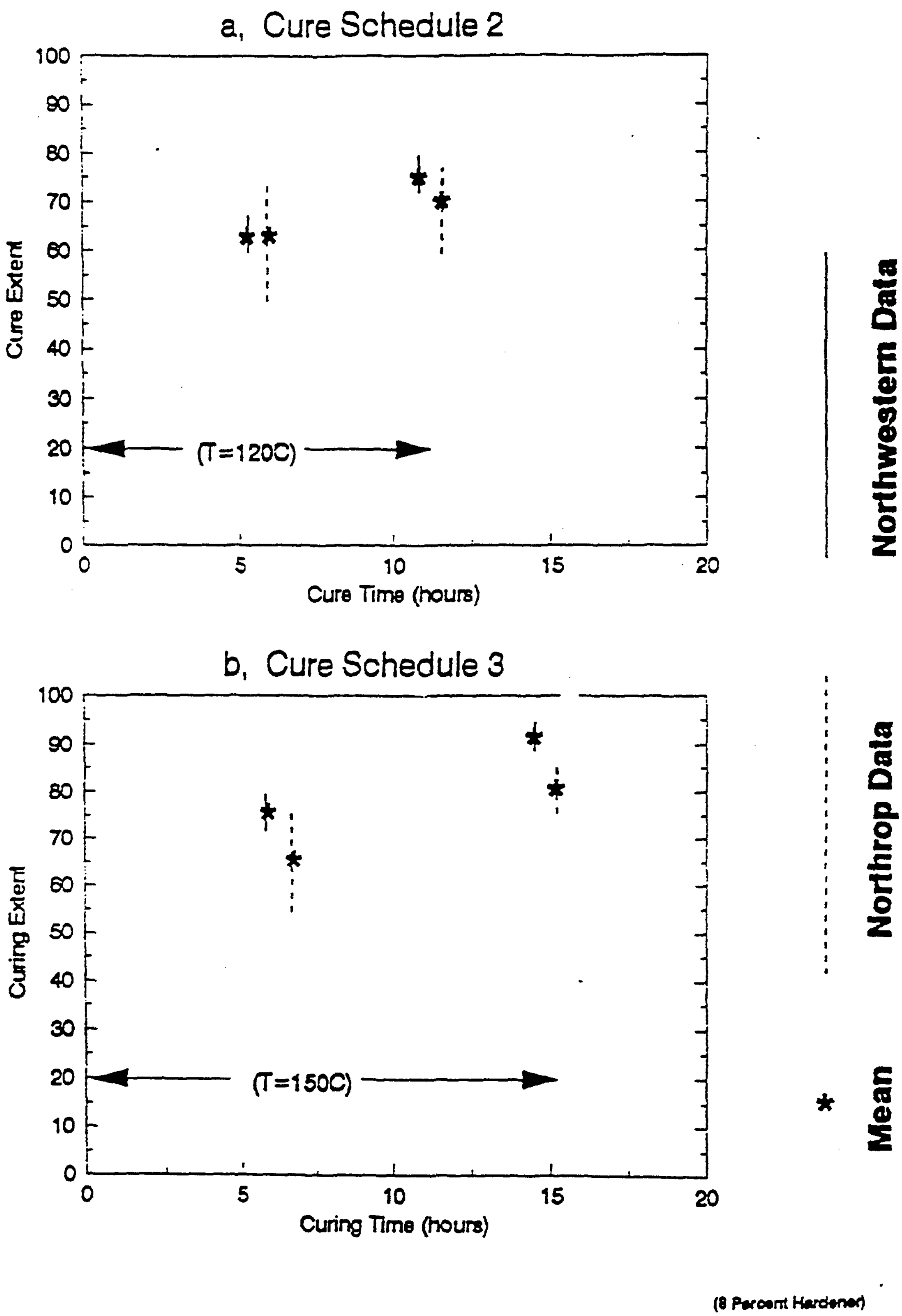


Figure 6.1-8 **Curing Extent via FTIR (95% confidence intervals)**

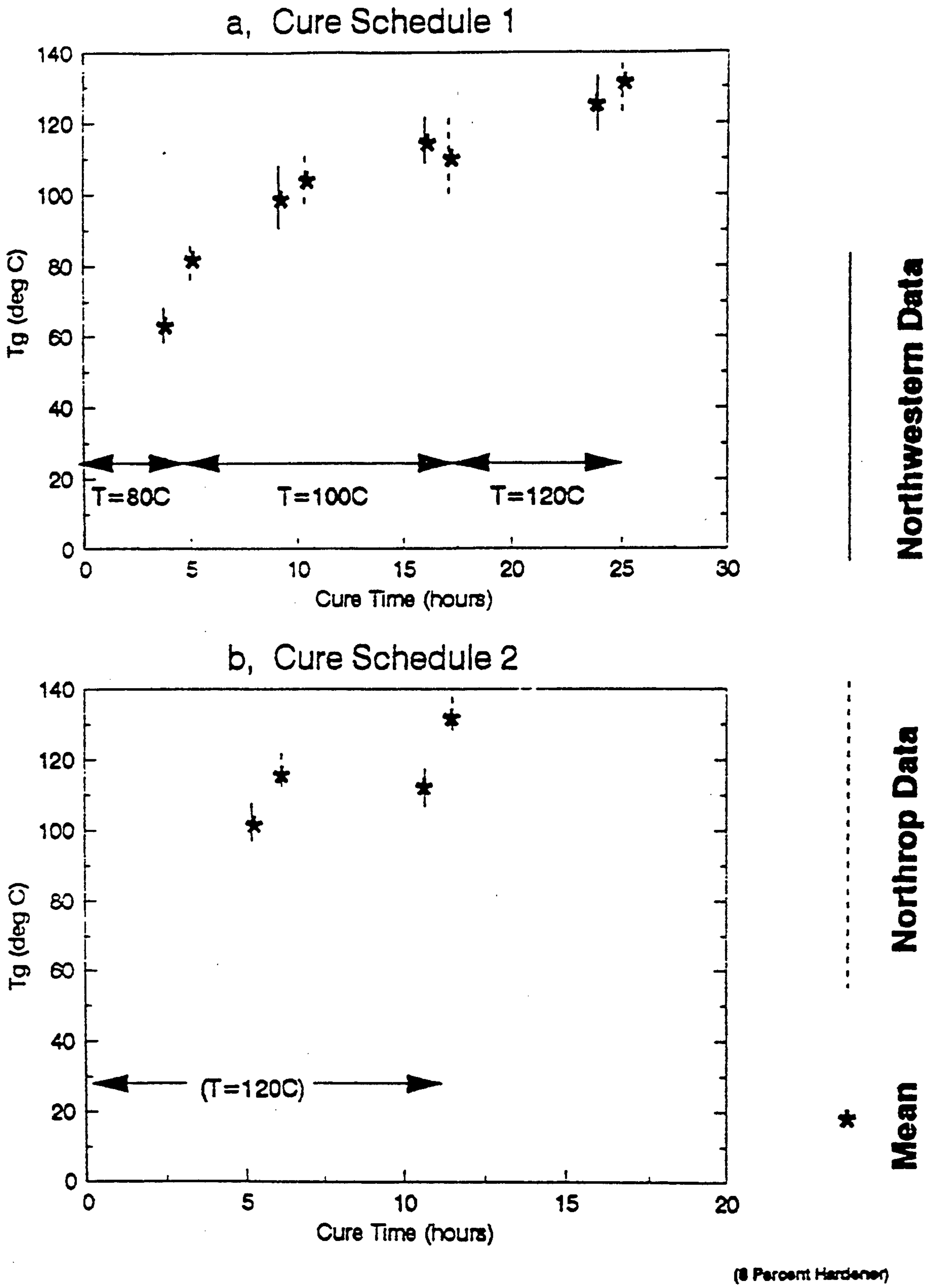


Figure 6.1-9 **Glass Transition Temperature (Tg) versus Cure Schedule (95% Confidence Intervals)**

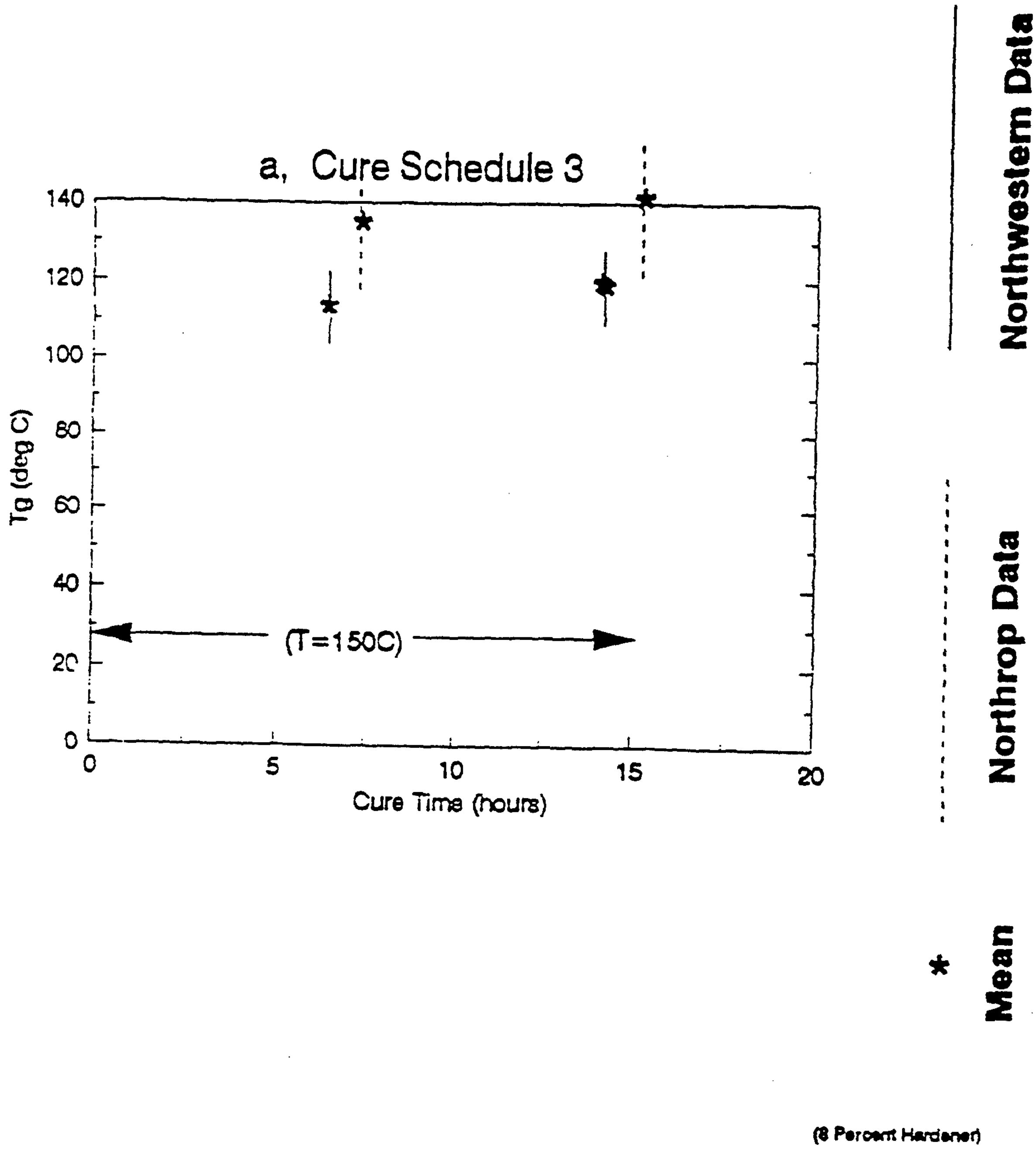


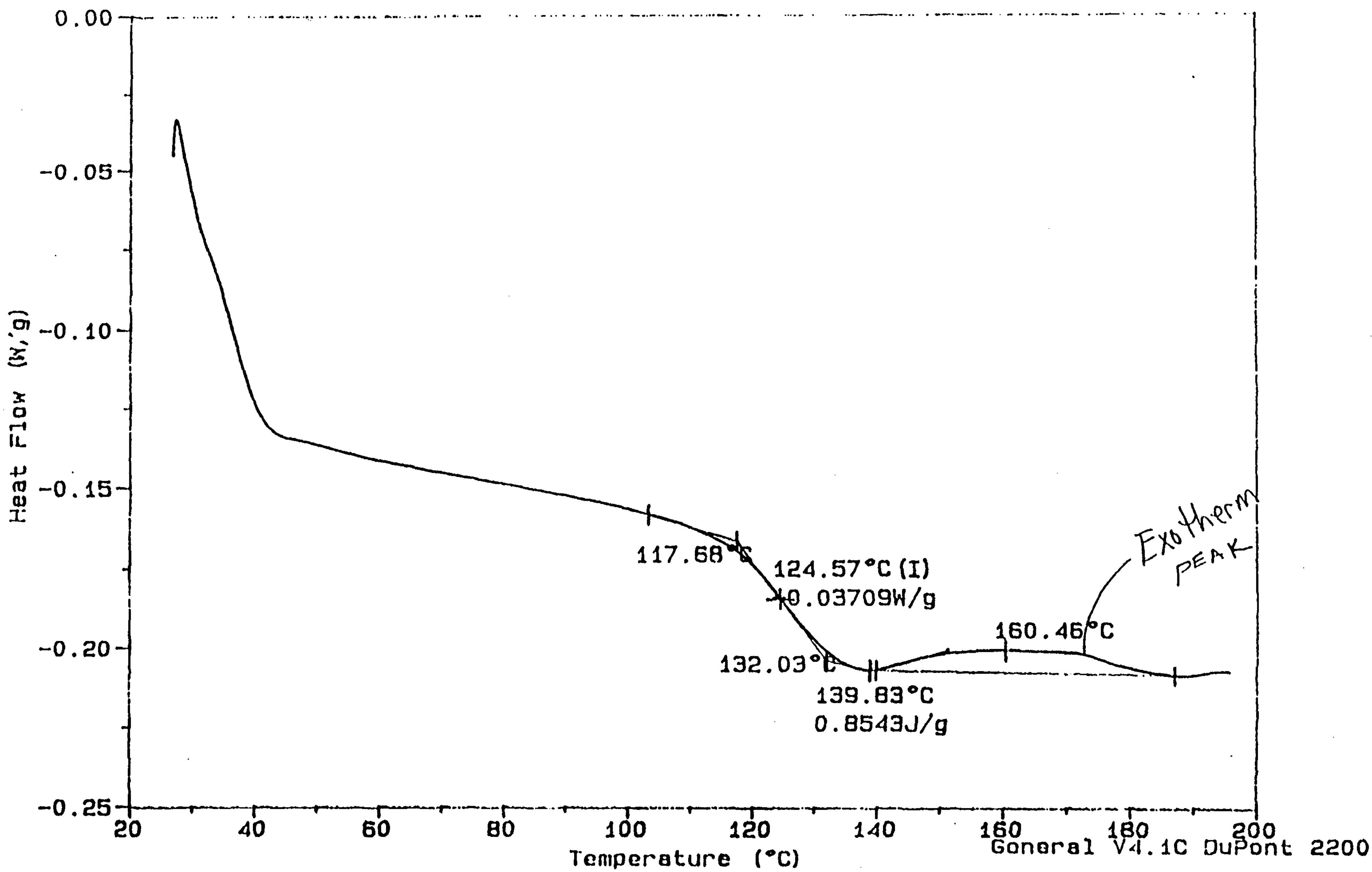
Figure 6.1-10 **Glass Transition Temperature (Tg) versus Cure Schedule (95% Confidence Intervals)**

Figure (-11

DSC

Sample: S1C28T12
Size: 11.5970 mg
Method: 30° TO 200° @15°C/MIN
Comment: 80CC/MIN N2 10X

File: C: DSC-1C2812.01
Operator: B.SPILLAR
Run Date: 26-May-93 12:52



6.1.2.2 Cure Optimization

Cure optimization studies of Emerson & Cuming Stycast 2651MM were conducted using two catalyst levels and matrixed with three cure schedules to provide a varied product base for measuring extent of cure. Figure 6.1-25 is a test matrix illustrating the catalyst/cure combinations and the characteristics measured. Figure 6.1-26 illustrates early comparisons of round-robin data from Northwestern University and Northrop Grumman ESID. In both figures (a and b) the NGESID results are enclosed in brackets while the NU data are not. Figure 6.1-26a looks at cure extent determined via Fast Fourier transform InfraRed spectroscopy (FTIR) and shows about a 15 percent difference in calculated cure extent between the two measuring sites. Figure 6.1-26b begins to examine the degree of cure as determined by a shift in the glass transition temperature (Tg) via Differential Scanning Calorimetry (DSC). Description, results and conclusions are as follows:

> A Fourier Transform-InfraRed (FTIR) spectoscopy study measures depletion of the reactive oxirane portion of the epoxy molecue as a "degree of cure" technique. Figures 6.1-27 and 6.1-28 graphically portray the test results. Figure 6.1-27 shows faster cure for the eight percent catalyst concentration (Fig 6.1-27b) which is expected since this is the supplier recommended mix ratio and cure schedule employed at NGESID for several years and illustrates the incomplete cure discovered early in this MANTECH program. Figures 6.1-28a and 6.1-28b look at the eight percent concentration case for two additional cure schedules. Figure 6.1-28b illustrates the more completely cured case (cure schedule 3) which was used when constructing the phase II hardware. Data taken at both NU and NGESID overlap when 95 percent confidence intervals are added. This FTIR procedure is difficult to conduct and must be done very carefully.
>
> Figures 6.1-29 and 6.1-30 illustrate the change to glass transition (Tg) resulting from the same three cure schedules for an eight percent catalyst concentration. Again, cure schedule 3 indicates that schedule 2 was incomplete.
>
> Figure 6.1-31 is a classic Differential Scanning Calorimeter (DSC) run of the Stycast 2651MM material showing an exotherm peak in excess of 140 degrees C., again illustrating that cure schedule 2 is insufficient.

Figure 6.1-25, Status - Cure Completeness Program

(STYCAST 2651MM)

TEST	SMPL SIZE	8% Catalyst CURE 1	8% Catalyst CURE 2	8% Catalyst CURE 3	7% Catalyst CURE 1	7% Catalyst CURE 2	7% Catalyst CURE 3	COMMENTS
FT-IR SPECTROSCOPY	6	C/C	C/C	C/C	C/C	C/C	C/C	Data collected at six hour intervals
EQUILIBRIUM SWELLING	6	C/E	C/E	C/E	E	E	E	Extensive Development Required
Tg (via DSC)	6	C/C	C/C	C/C	C/C	C/C	C/C	Data collected at six hour intervals
CURE HEAT (via DSC)	6	/C	/C	/C	/C	/C	/C	Data collected at six hour intervals
WEIGHT LOSS (via TGA)	6	*/C						* Alternate Cure
VOLUME RESISTIVITY	6	/C	E	E	E	E	E	Impractically Long Test Time

CURE 1, 5 HRS @ 80 C PLUS 12 HRS @ 100 C PLUS 8 HRS @ 120 C (Northrop Cure)
CURE 2, 12 HRS @ 120 C (Under Cured)
CURE 3, 15 HRS @ 150 C (Over cured)

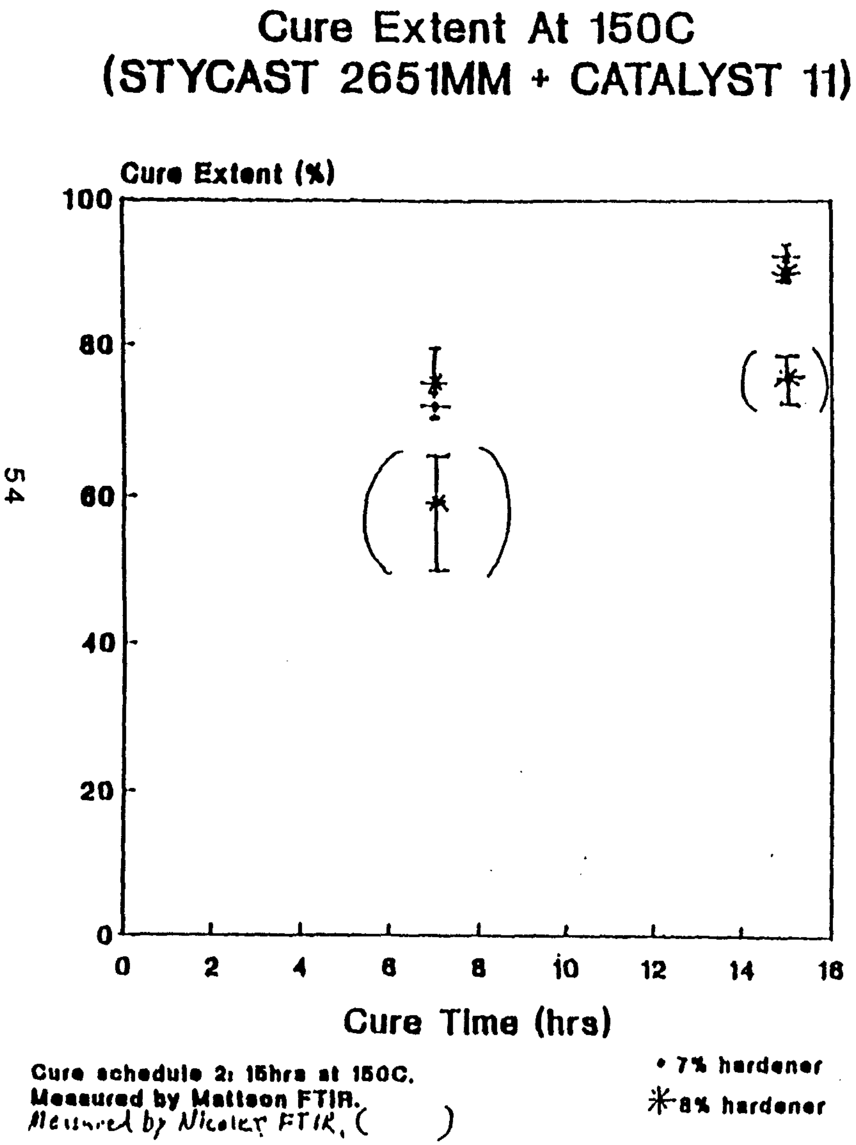
* Alternate Cure, 8 HRS @ 100 C PLUS 12 HRS @ 120 C PLUS 15 HRS @ 150 C

C => Test Completed
P => Test In Progress
S => Samples In Preparation
E => Ended-Too Costly

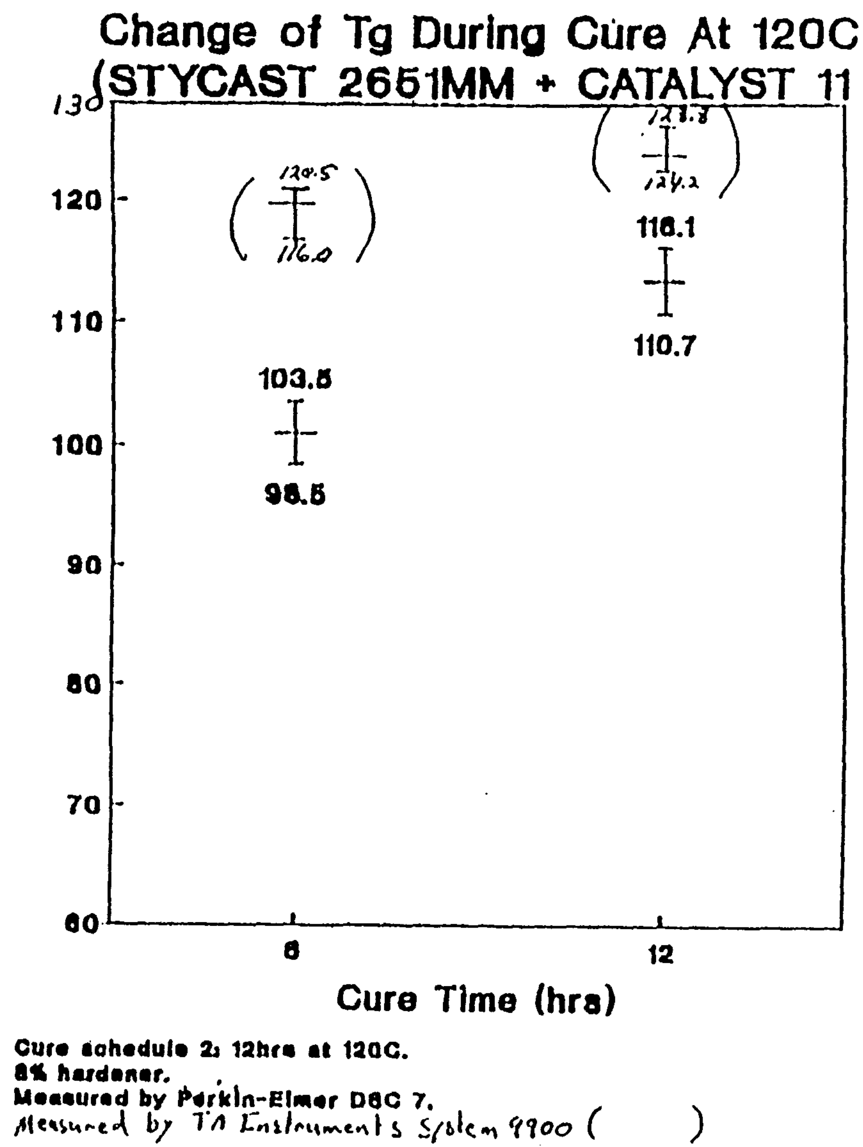
NU/NOR

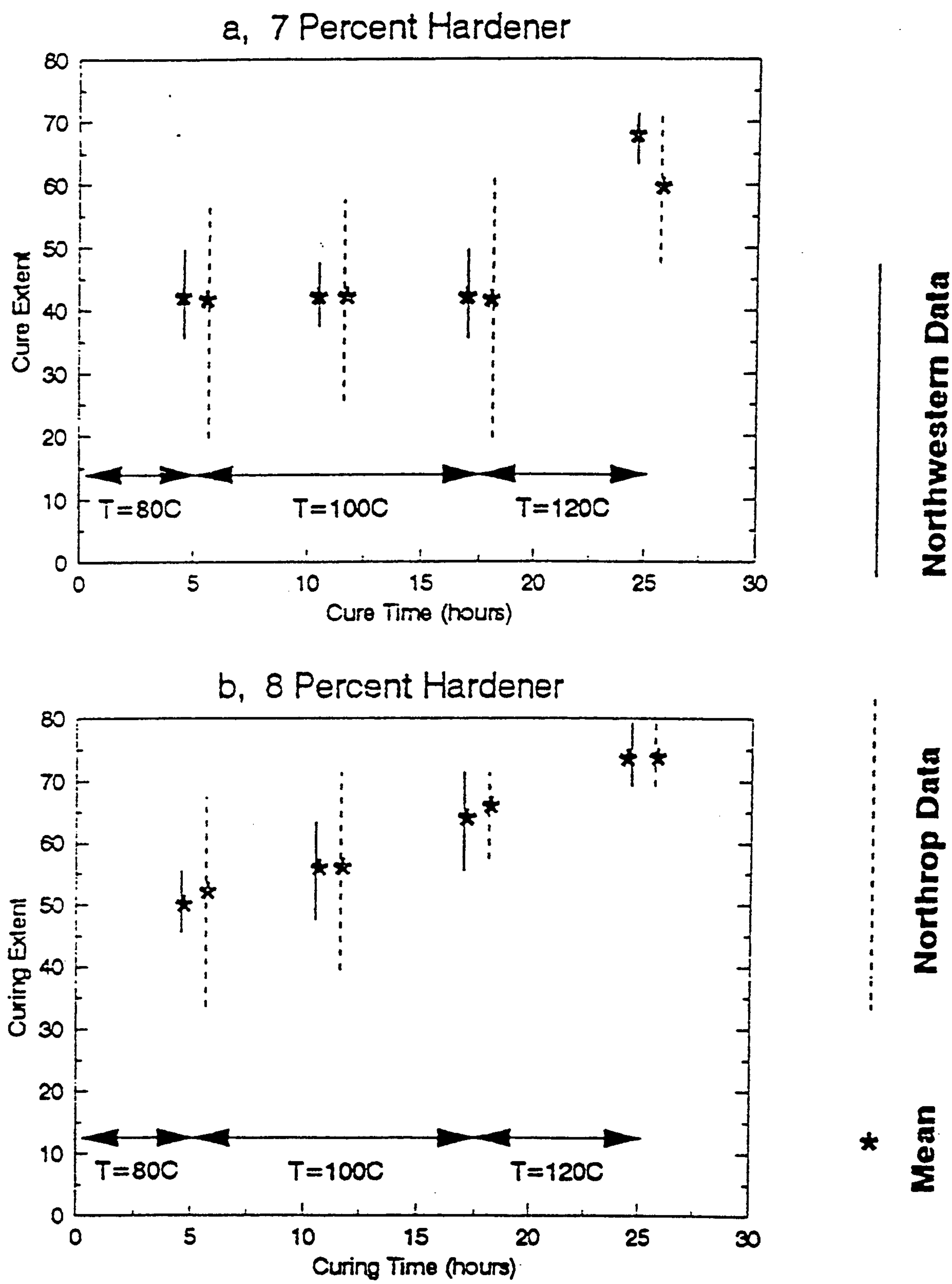
Figure 6.1-26, Status - Cure Completeness Comparisons

6.1-26a, FTIR Cure Extent



6.1-26b, DSC Cure Extent





(Cure Schedule 1)

Figure 6.1-27 **Curing Extent via FTIR (95% confidence intervals)**

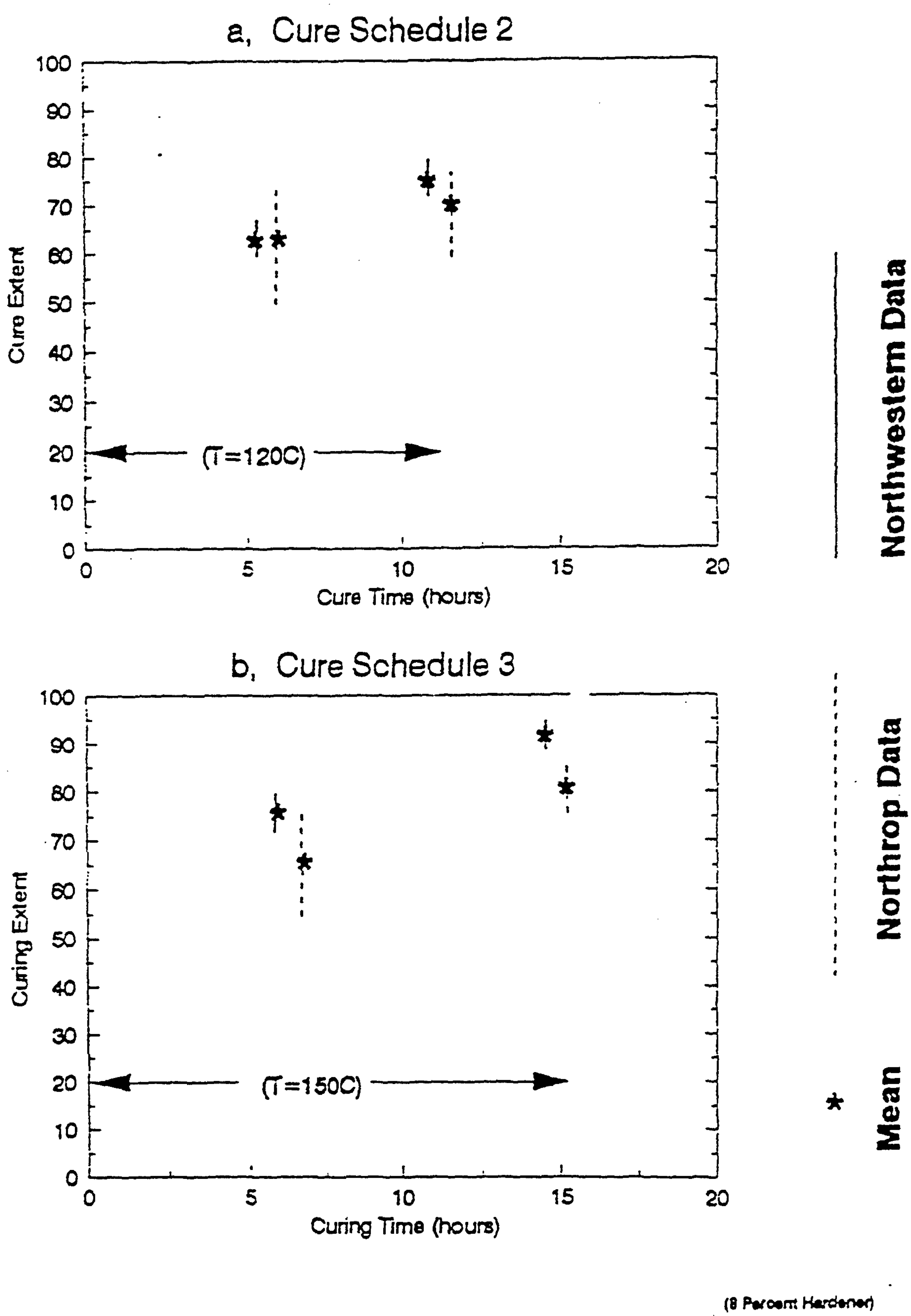


Figure 6.1-28 **Curing Extent via FTIR (95% confidence intervals)**

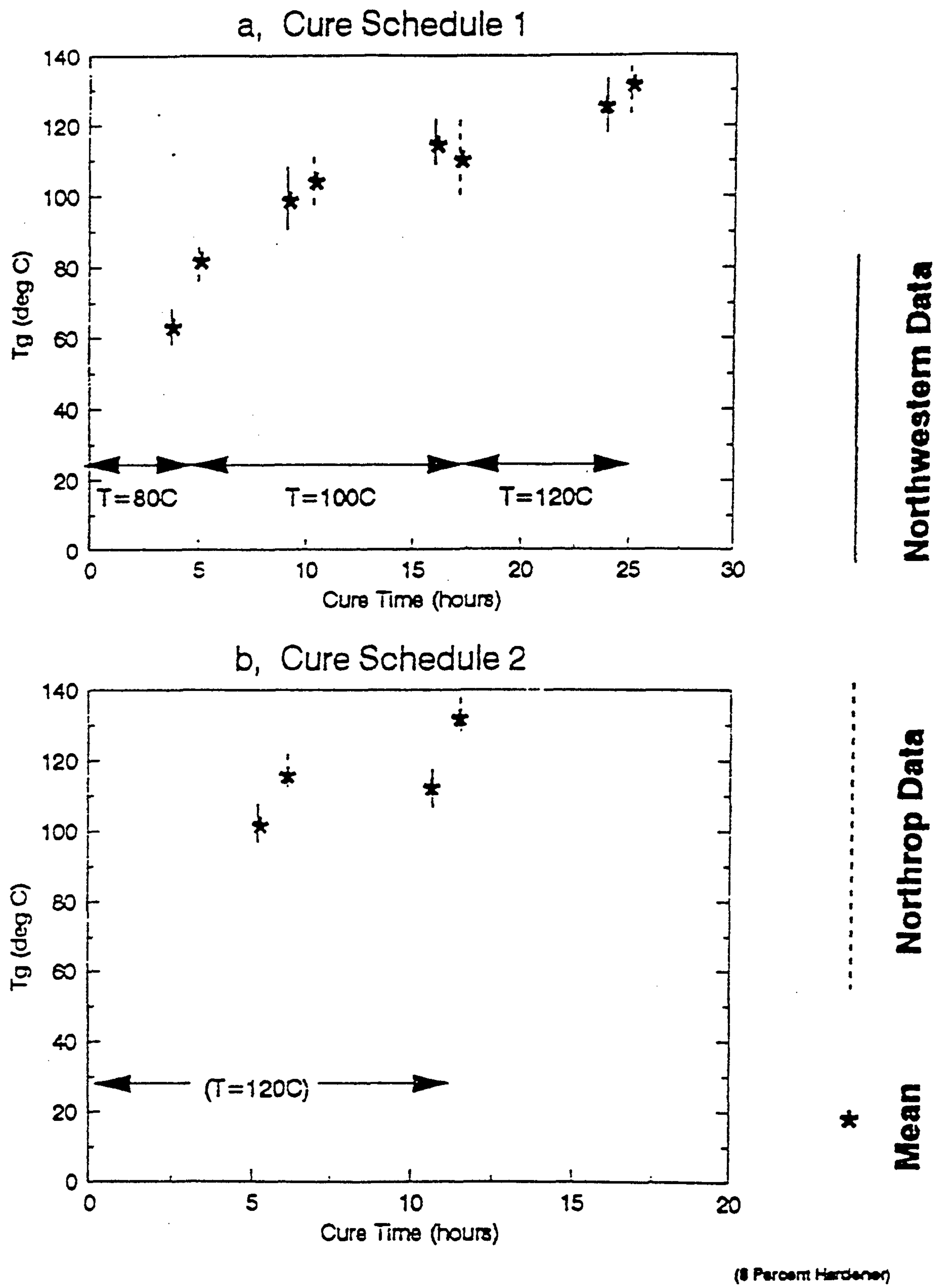
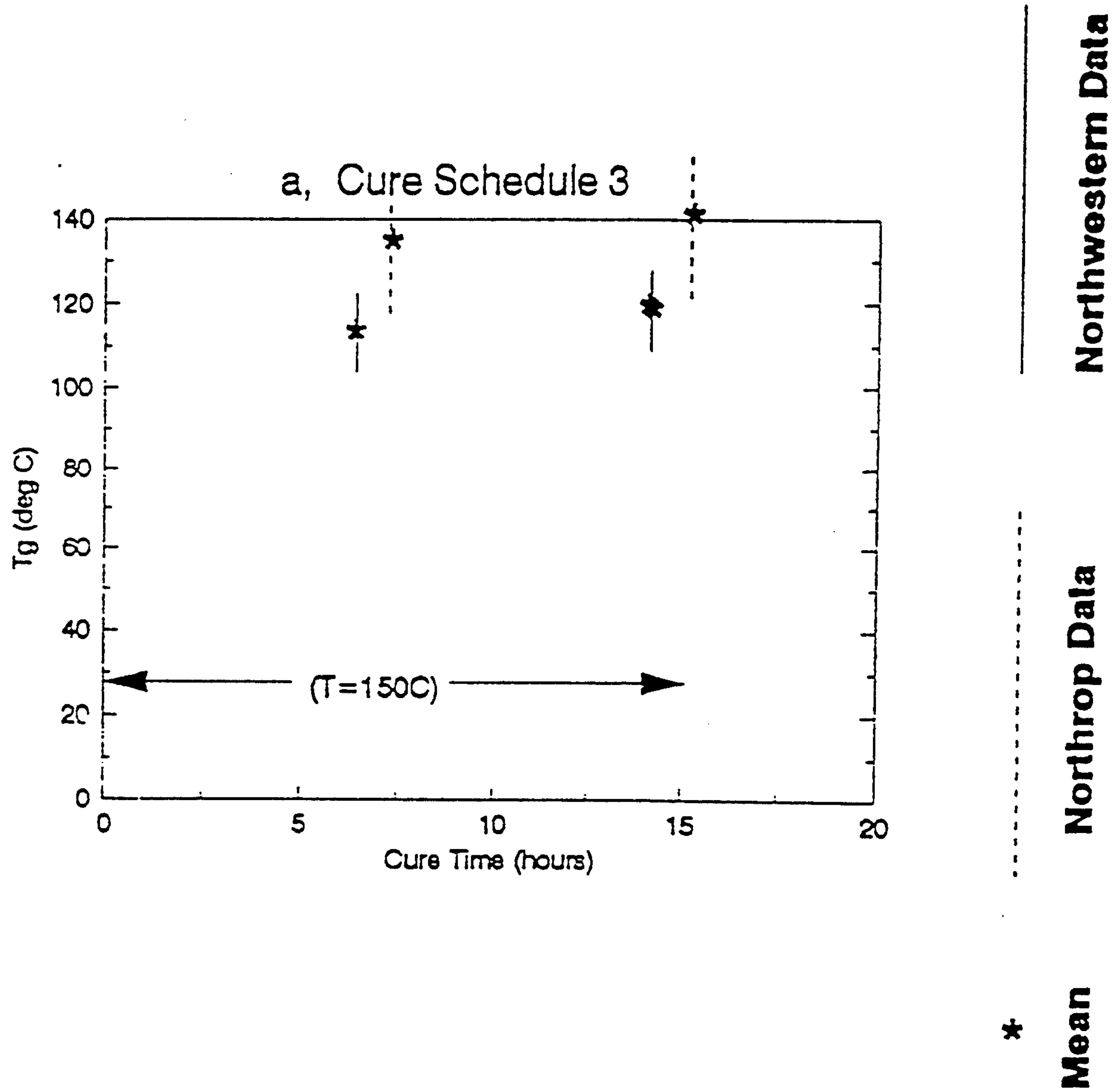


Figure 6.1-29 **Glass Transition Temperature (Tg) versus Cure Schedule (95% Confidence Intervals)**



(8 Percent Hardener)

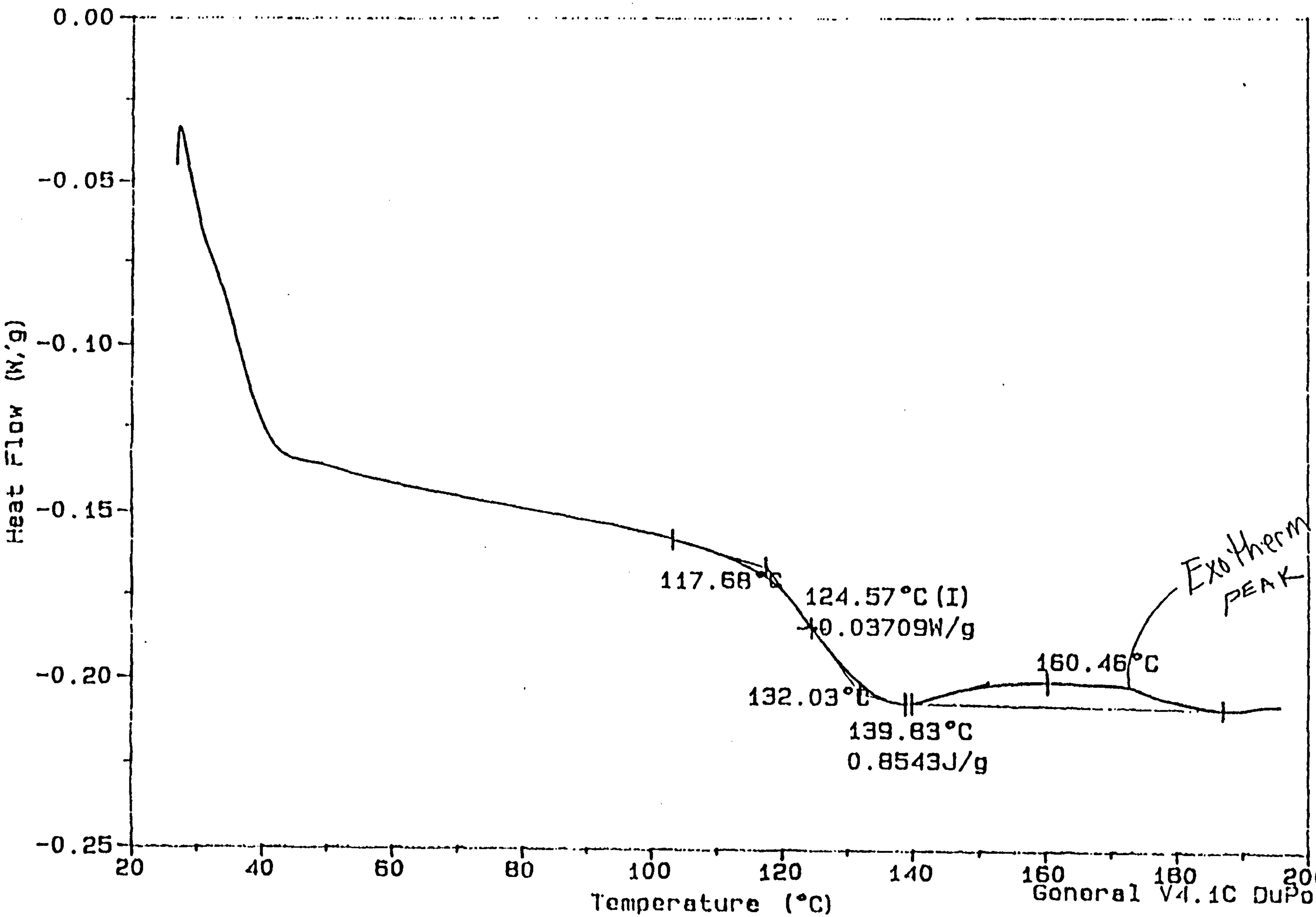
Figure 6.1-30 **Glass Transition Temperature (Tg) versus Cure Schedule (95% Confidence Intervals)**

Figure 6.1-31

Sample: S1C28T12
Size: 11.5970 mg
Method: 30° TO 200° @15°C/MIN
Comment: 80CC/MIN N2 10X

DSC

File: C:DSC-1C2812.01
Operator: B.SPILLAR
Run Date: 26-May-93 12:52



General V4.1C DuPont 2200

Note from Figure 6.1-25 that efforts to monitor extent of cure via changes in volume resistivity and solvent swelling were dropped as being overly time consuming. in the case of volume resistivity, it simply took to long (several hours) for readings to stabilize. The solvent swelling program was always understood to be highly theoretical in nature, but of enough utility to warrant inclusion in the MANTECH program. This may still be true but it became obvious that too much additional work would be required to reach conclusions that could be considered useful in a manufacturing environment.

The following is a cross reference guide to specific program details, procedural details and reference information in Volume 2, 3, and 4 respectively that relate to epoxy materials:

Volume 2 Program Details

Section 1.2.2 Analysis of Variance and Section 1.2.3 Statistical Test Plan for Characterizing Material and Components.
These sections provide guidelines in developing and creating a statistically significant test plan and analyzing the data.

Section 2.0 Characteristics of Encapsulants
This section discusses the desirable characteristics of encapsulants and their related attributes. Several encapsulant material classes are qualitatively evaluated against the more common encapsulant parameters. Standard test methods are listed for encapsulant properties.

Volume 3 Procedural Details

Section 2.1 Designing a Significant Experiment
This section provides a methodology to designing a statistically significant experiment including; sample size, sample randomization, and analysis of the data.

Section 2.2 Mechanical Characterization of Silicone Rubber
A method is provided for making precise measurements for the Elastic Modules and Poisson's Ration of elastomeric materials in the low strain range.

Section 2.7 Materials Specification Guidelines
This section provides recommendations and guidelines for preparing a detailed encapsulant material specification.

Section 2.8 Material Specification
This material specification is for silicone, Eccosil 4952N. However, it provides useful information in developing a specification for epoxy encapsulants.

Section 3.0 Epoxies/Urethanes
This section lists 16 tests that are recommended for a comprehensive evaluations of an epoxy or urethane for application to high voltage encapsulation. Stress aging and effects of cure on performance are discussed.

Volume 4 Reference Material

Section 1.4 Encapsulated Electrode Pair Test Structures
A model test structure to evaluate corona and electrical breakdown characteristics of various encapsulants is provided.

Section 2.1 Corona and Breakdown Performance of Specific Materials
This section provides the results of corona and breakdown performances testing using the model test structure described in Section 1.4.

Section 2.6 Electrical; Mechanical and Thermal Properties of Specific Encapsulants
Characterization data for 17 materials is provided.

6.2 Components

6.2.1 High Voltage Connectors

Four objectives were established for the high voltage connector evaluation program conducted by connector manufacturer, Reynolds Industries Inc.:

a. Measure Connector Aging as a Function of Applied Stress
b. Compare Performance of Bonded Fit Vs. Slip Fit Assembly Technique
c. Measure Reliability and Performance Affects of Mating and Unmating
d. Measure Reliability and Performance Affects of Partially Mated Connectors

Figure 6.2-1 shows a cross-section of the connector contact assembly used in the study program - a 15KVDC rated assembly that is considered typical for use in operating systems up to about 12KVDC. The cross-section depicts one contact of what is generally a multi-pin connector (Northrop Grumman uses this system in a 12 pin configuration). The figure illustrates the contact in the mated condition. Objective b, above, refers to the silicone cable seal (see figure) and whether the seal should be a slip fit between the Teflon (FEP) wire on the inside and the contact nose insulator on the outside or whether the seal should be adhesively cemented in place ie., bonded to the teflon wire and nose insulator.

As described in Executive Summary Section 5.2.1, four test conditions were established to evaluate performance and reliability of the connector. Figure 6.2-2 gives the details of test conditions 1 and 2 (Group 1 and Group 2). Group 1 testing used four sets of twelve contacts each arranged in a matrix program to compare bonded and slip-fit approaches under temperature and under temperature/altitude/voltage conditions. Each set of twelve was submitted to thermal cycling as detailed in the figure. The temperature only category covered the full cold-hot range. Insulation resistance measurements and partial discharge measurements were made during each cycle. The latter set-up is shown in Figure 6.2-3. Initial and concluding tests of contact resistance and electrical continuity were also made. Group 2 fabrication and testing was identical to Group 1 in all aspects except for the application of 18KVDC (20% overstress).

Test condition 3 (Group 3) is given in Figure 6.2-4. Two sets of 48 contacts each were tested as shown in the figure. Note that all environmental cycles are full temperature, altitude, voltage stressed. Each cycle had an added step of unmating and re-mating the connector to simulate extreme field use.

Test condition 4 (Group 4) is shown in Figure 6.2-5. Three sets of 12 contacts each were positioned from fully engaged, set A, to 0.110 inches of gap for set C. Although difficult to believe that a HV connector set would not be fully mated, it was never-the-less prudent to conside "what if" scenarios when evaluating reliability and performance. Gap details are given in Figure 6.2-6.

CROSSECTION OF TEST SAMPLE IN MATED CONDITION

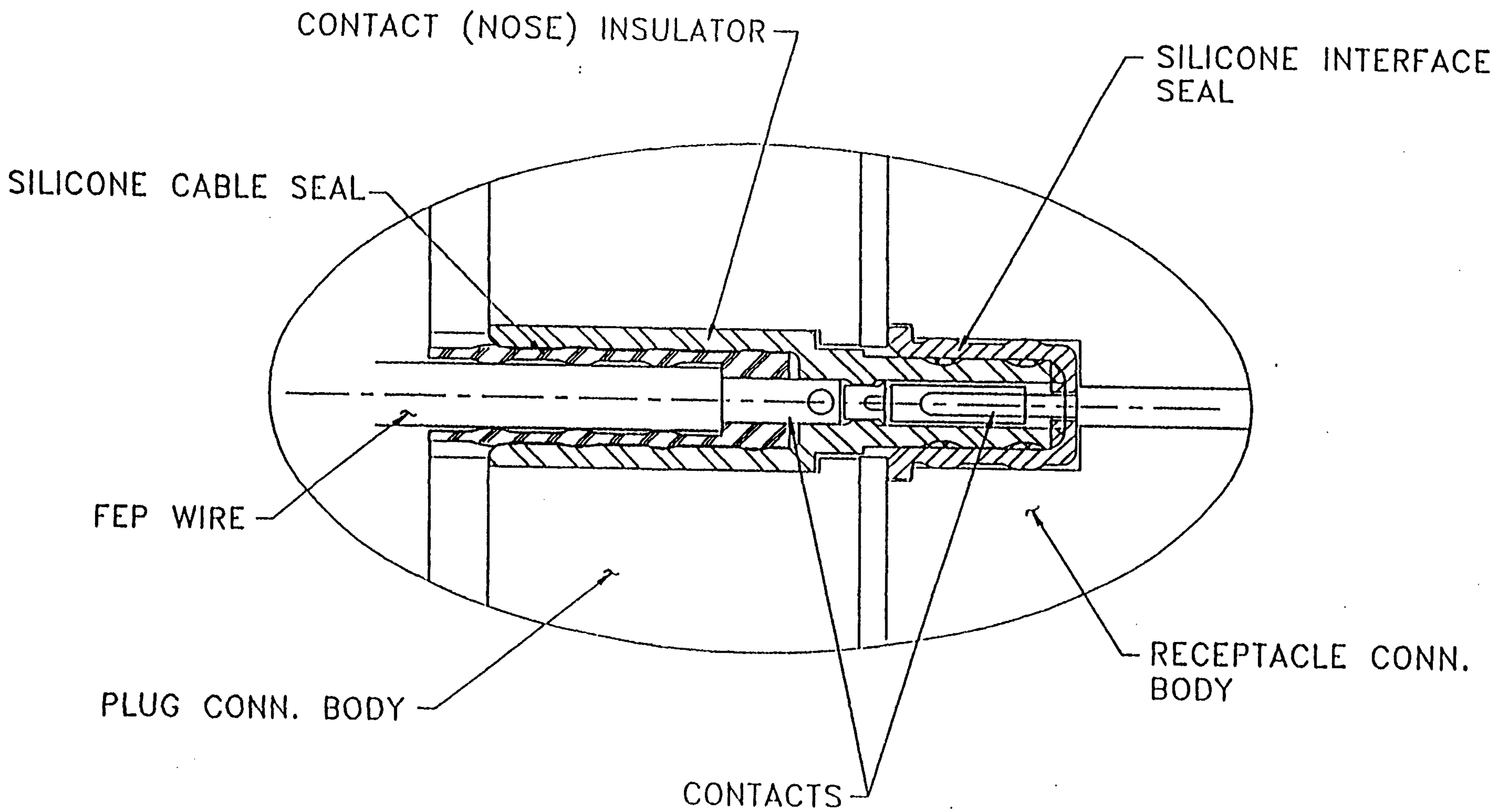


Figure 6.2-1 Connector Contact Assembly

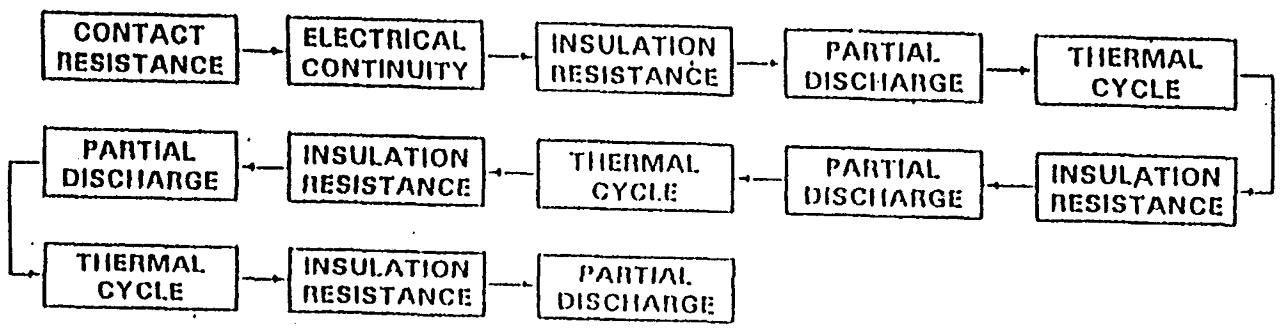
HIGH VOLTAGE CONNECTOR TEST PROGRAM

GROUP 1, BASIC CONNECTOR RELIABILITY MATRIX:

	SAMPLE SIZE	HV (dc)	BONDED ASSY	SLIP-FIT ASSY	TEMP ONLY	TEMP, ALT, VOLTAGE*
A.	12	15kv	x			x
B.	12	15kv	x		x	
C.	12	15kv		x		x
D.	12	15kv		x	x	

GROUP 2, STRESSED CONNECTOR RELIABILITY MATRIX:

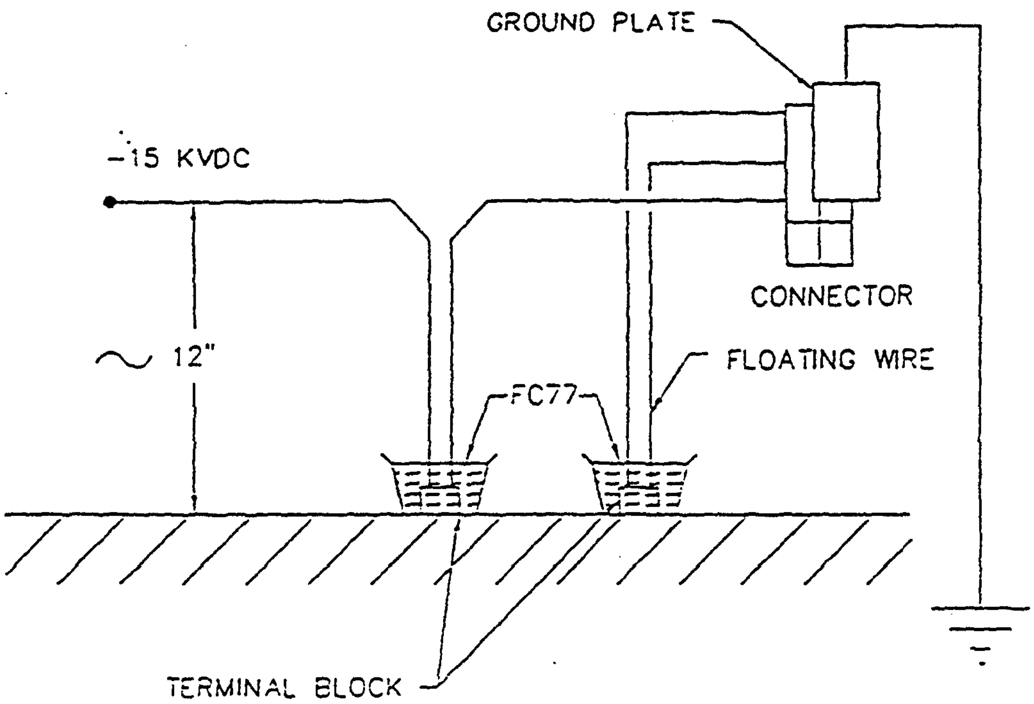
SAME AS ABOVE EXCEPT 18kv APPLIED



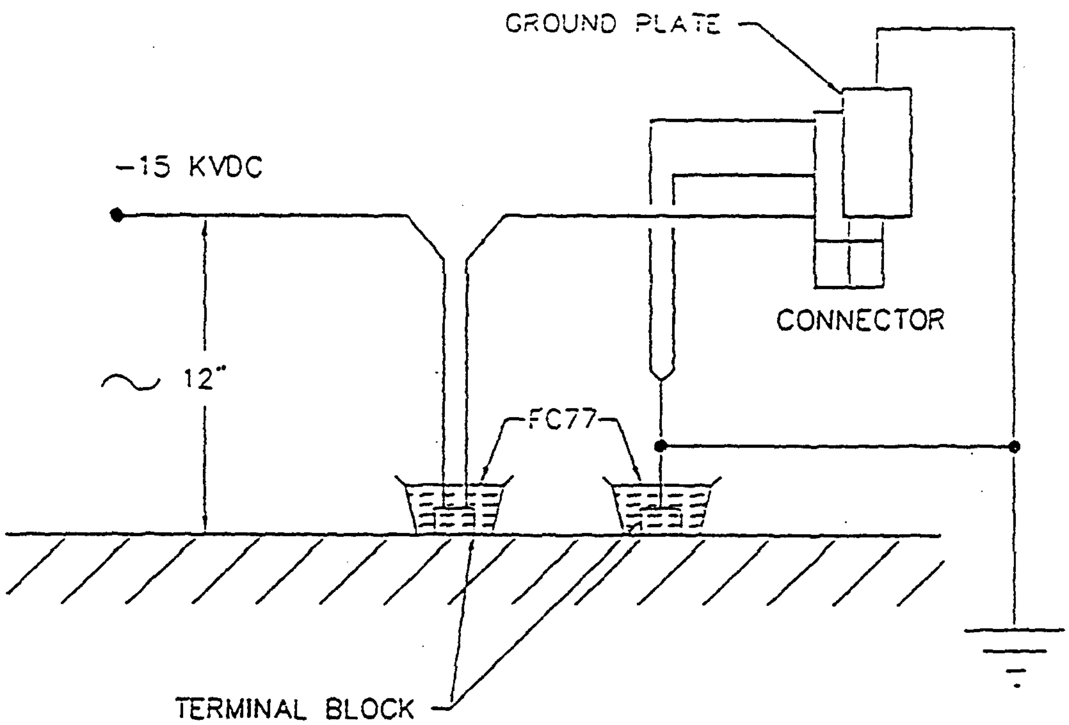
*Thermal Cycle: 4 hours @ -65C, 4 hours @ +125C with continuous application of high voltage and altitude (35 Torr) during the cycle.

Program Duration: 75 cycles

Figure 6.2-2 Test Conditions 1 and 2



Floating



Ground

Figure 6.2-3 Partial Discharge Test Set-Up

HIGH VOLTAGE CONNECTOR TEST PROGRAM

Group 3, Mating/Unmating Connector Reliability Matrix:
(with improved cable pre-conditioning)

	Sample Size	HV (dc)	Bonded Assy	Slip-Fit Assy	Temp, Alt, Voltage	Number Of Cycles
A.	48	15kv	x		x	75
B.	48	15kv		x	x	75

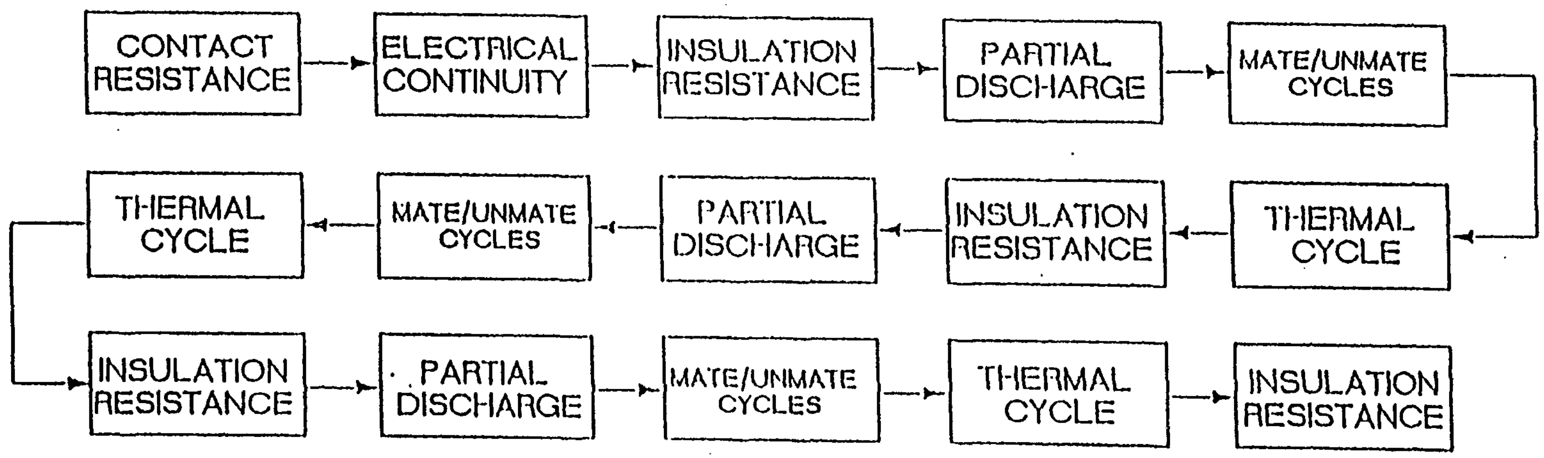


Figure 6.2-4 Test Condition 3

Group 4, Partially Mated Connector Reliability Matrix:

	Sample Size	Gap To Ground Plane	Temp, Alt, Voltage	Number Of Cycles
A.	12	0	x	50
B.	12	0.050 in.	x	50
C.	12	0.110 in.	x	50

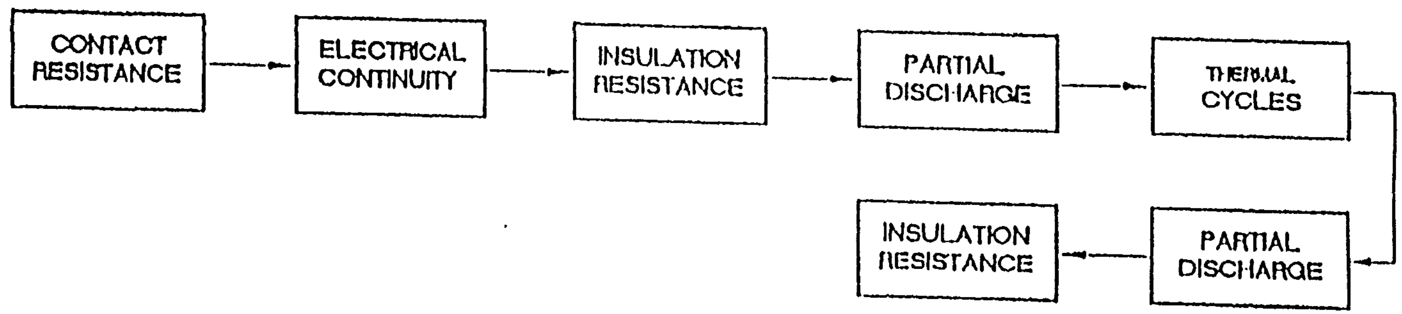


Figure 6.2-5 Test Condition 4

GROUP 4 TEST SAMPLE ARRANGEMENT

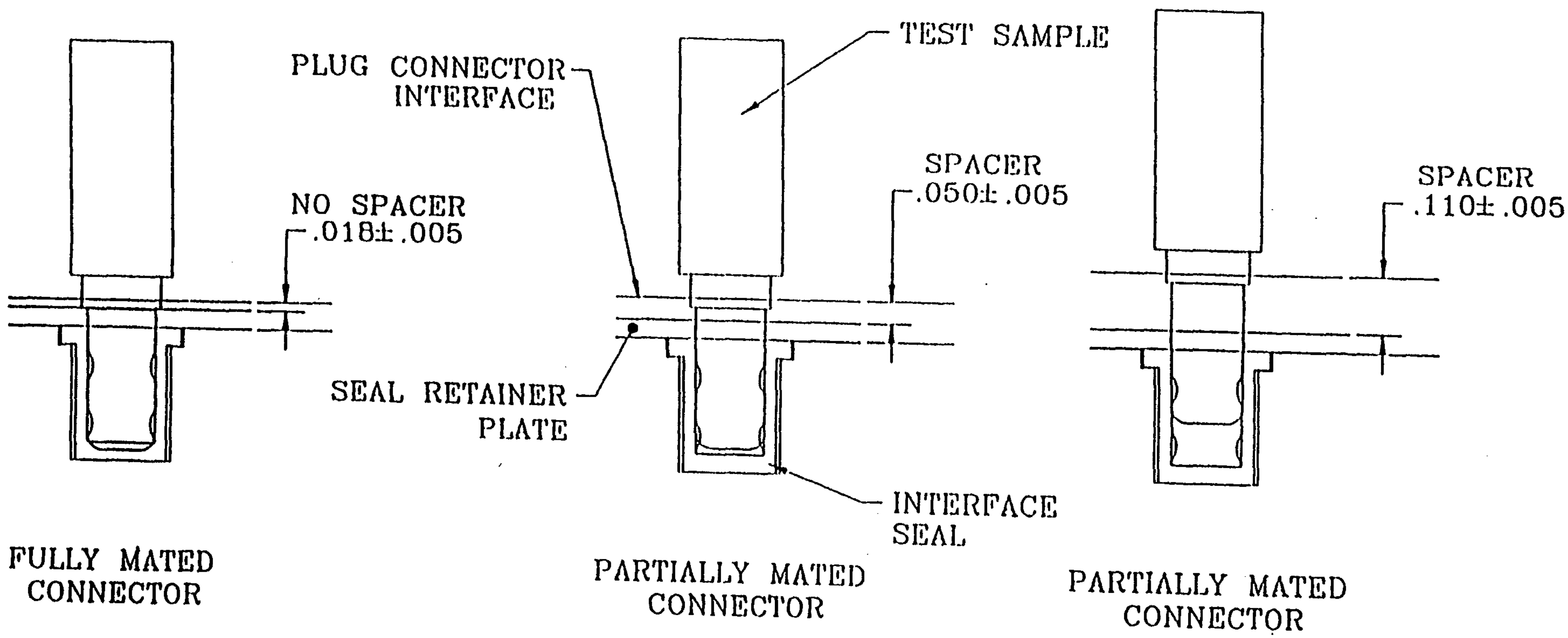


Figure 6.2-6 Test Condition 4 Gap Details

Figure 6.2-7 summarizes the results on all four test groups. Within our test criteria of 75 cycles (close to a month of testing with 8 hours per test cycle), the basic connector performed well at 15KV, showed an increased failure rate at 18KV with the slip fit cable seal more prone to failure than the bonded seal and continued to show rising failure rates for the mate-unmate and partially mated test conditions. Note the overiding failure cause is shrinkback of the teflon on the wire. This subsequently exposes the center conductor to the environment and eventually causes failure - see Figure 6.2-8. Note from 6.2-8 that the cable seal stays firmly in place over the teflon but slips on the contact nose. Discussions with wire suppliers and manufacturers identified the wire extrusion process and the subsequent stresses established in the FEP as a result of that process, as the determining factor in wire performance over temperature. It appears a slow, controlled temperature extrusion process is the recommendation for minimizing residual stresses. At a cost sacrifice, minimum shrinkback (quantified as required) can be specified on purchase drawings. Further results from the tests are indicated under Observations in Figure 6.2-7. Reynolds now recommends an isopropyl alcohol rinse when unmating and remating connectors as a result of the debris creation. The connector life test procedure is documented in Volume 3, Section 1.4.1.

HIGH VOLTAGE CONNECTOR TEST PROGRAM

	FAILURES	CAUSES	CONDITIONS/COMMENTS
GROUP 1 (48 pcs, 15kv)	3	INSULATION SHRINKBACK	FAILURES OCCURED AFTER 75 CYCLES
GROUP 2 (48 pcs, 18kv)	16	INSULATION SHRINKBACK	5 BONDED, 11 SLIP FIT ALL TEMP/ALT/VOLTAGE
GROUP 3 (96 pcs, mate/ unmate)	37	30 INSULATION SHRINKBACK 7 DEBRIS	
Group 4 (36 pcs, partially mated)	24	INSULATION SHRINKBACK	

OBSERVATIONS:

1. CORONA MEASUREMENT WAS NOT USEFUL AS AN INDICATOR OF DETERIORATION.
2. THE CONNECTOR INTERFACE SURFACES REMAINED IN GOOD CONDITION.
3. IT IS NOT POSSIBLE TO CONDITION FEP INSULATED HV WIRE TO A STATE WHERE FURTHER INSULATION SHRINKBACK WITH THERMAL CYCLING DOES NOT OCCUR.

Figure 6.2-7 Summary Of Test Results

EFFECT OF WIRE INSULATION SHRINKAGE

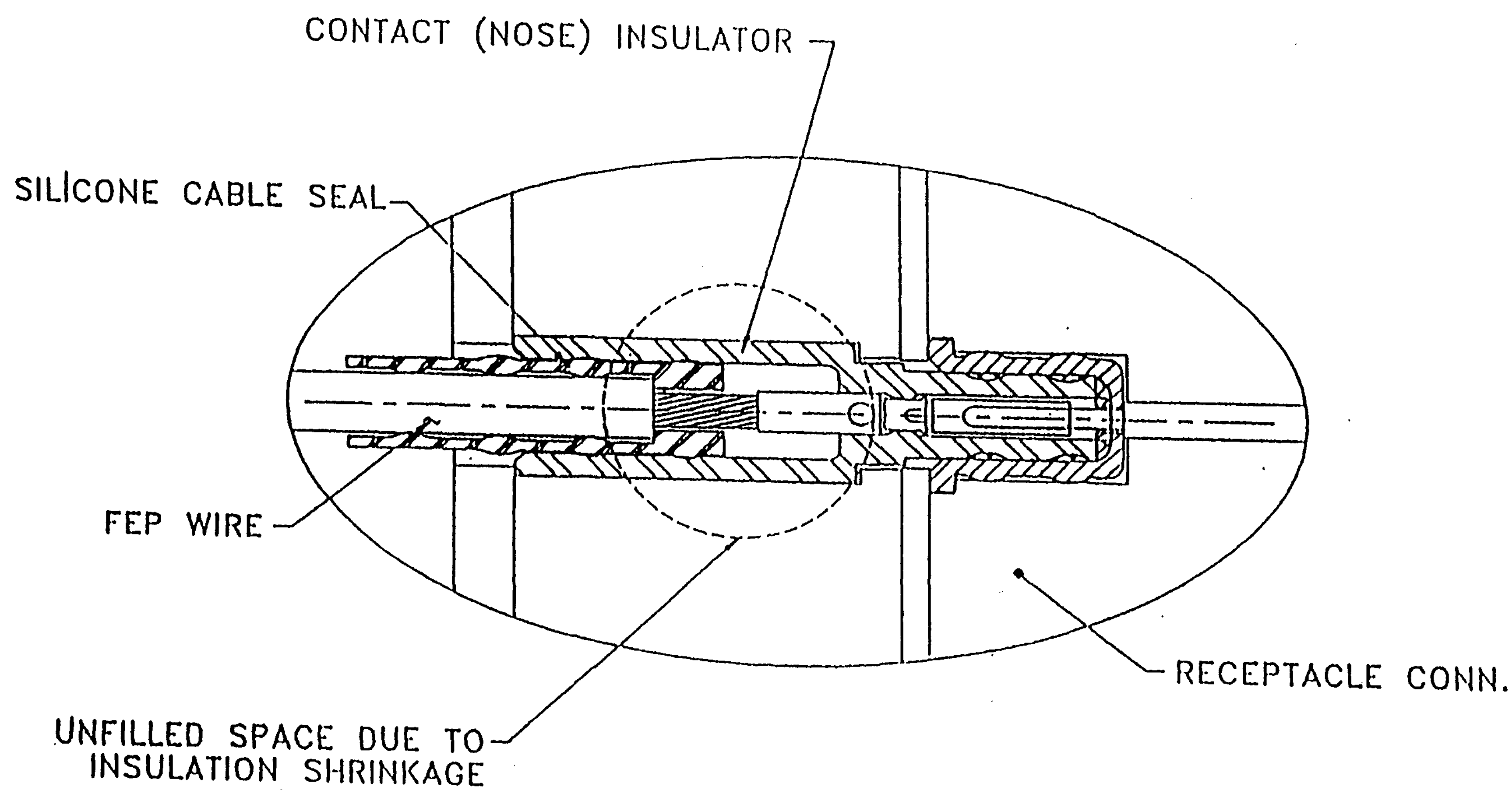


Figure 6.2-8 Connector Contact Assembly After Test

6.2.2 Capacitors

6.2.2.1 Ceramic

The quality of off-the-shelf ceramic high voltage capacitors, tested under stress, occupied an important part of this program. These components have, historically, proven troublesome when purchased in quantities suitable to support a manufacturing program. Specifications and acceptance requirements are frequently inadequate to an extent that good parts are rejected and bad parts are accepted even though costly screening programs are in place. The intent of this particular effort is to promote a greater understanding of the effects of a true operational environment on the continued reliability of ceramic capacitors which, in turn, should guide the contractor to correctly qualify and specify the components for their particular application. The original goal had been to present detailed methods for qualifying and specifying these parts. Such a goal required that extensive life testing experiments be designed and implemented to measure MTBF with high confidence as a function of operating environment. These experiments were designed but the costs to implement them proved to be prohibitive and thus they were not implemented. However, a great deal of information was developed which demonstrates varying levels of degradation when testing in a stressed environment. Stress levels were intentionally limited to the normal operational environment (with the exception of life tests conducted at 1-1/2 times rated applied voltage) of aerospace hardware, i.e. there was no acceleration to abnormal stresses.

The testing program developed is illustrated in the flow diagram of Figure 6.2-9.

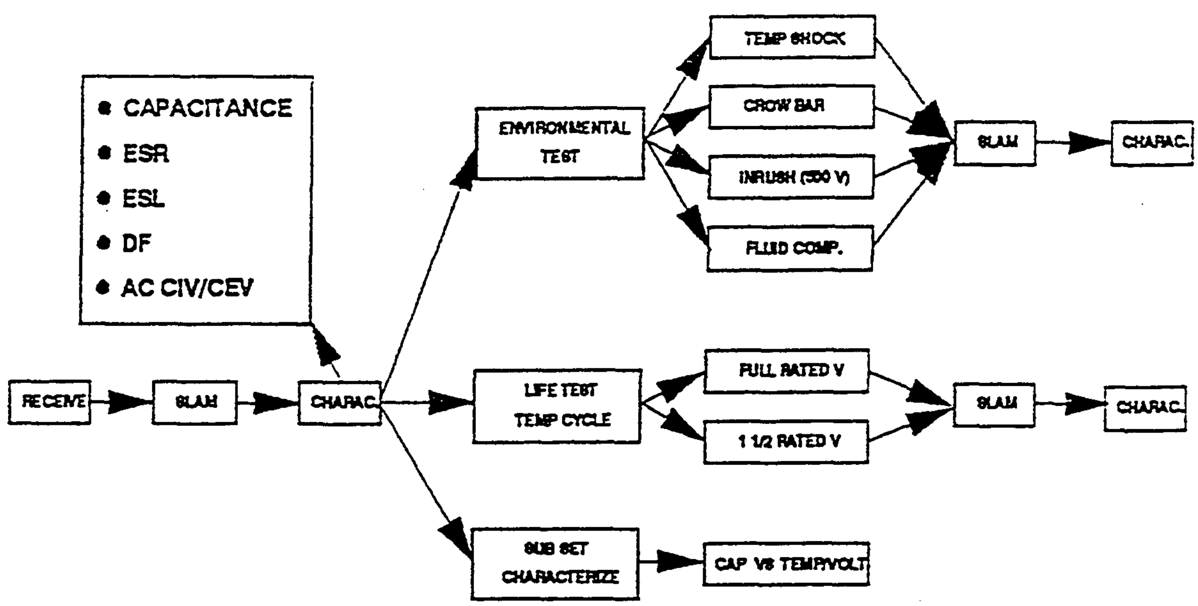


Figure 6.2-9 Ceramic Capacitor Test Program

Test items were received and subjected to an initial acoustical examination using a Scanning Laser Acoustical Microscope (SLAM). There were then characterized by evaluating the Capacitance, Equivalent Series Resistance (ESR), Equivalent Series Inductance (ESL), Dissipation Factor (DF), Corona Inception Voltage (CIV) and Corona Extinction Voltage (CEV). The items submitted to this test are shown in Table 6.2-1.

QUANT	SUPPLIER	CAP-UF	V RATING	DIELECTRIC	DIEL. TYPE	LAYERS	COATED
100	Supplier B	0.022	1,000	CERAMIC	X7R	1	N
100	Supplier C	0.022	1,000	CERAMIC	X7R	1	Y
100	Supplier A	0.024	1,000	CERAMIC	X7R	1	N
100	Supplier D	2.200	500	CERAMIC	X7R	2	N
100	Supplier E	2.200	500	CERAMIC	X7R	2	N
100	Supplier C	2.200	500	CERAMIC	X7R	10	N

Table 6.2-1 Capacitor Test Items

The results of the first SLAM test are summarized in Table 6.2-2. The column labeled as DEFECTS describe parts which contained areas in which acoustic energy did not transmit completely through the part. This test result can only be attributed to air gaps within the part which absorbed the energy to an extent that it was not detected on the exit side. These air gaps were considered to be cracks or delaminations, thus, defects. Note that defect rates as high as 14 percent of as-received parts were seen. The technique does not work with the 10 layer parts since each interface between sections is essentially an air gap.

SUPPLIER	VALUE	CERAMIC TYPE	LAYERS	QUANT TESTED	DEFECTS
Supplier E	2.2 UF, 500 V	X7R	2	100	14
Supplier D	2.2 UF, 500 V	X7R	2	100	1
Supplier A	.022 UF, 1000 V	X7R	1	100	11
Supplier B	.022 UF, 1000	X7R	1	100	10
Supplier C	.022 UF, 1000 V	X7R	1	100	0
Supplier C	2.2 UF, 500 V	X7R	10	5	

Table 6.2-2 Ultrasonic Scan Results

A subset of 10-12 of each part was then characterized for the voltage and temperature coefficients of capacitance. This data is summarized inFigure 6.2-10. Note significant differences between parts from various suppliers. Incidently the alphabetic references to suppliers remains consistent throughout these discussions. Supplier C is the same supplier C in all references. Interesting points fromFigure 6.2-10 show that parts from supplier A are not very sensitive to applied voltage but fairly sensitive to temperature effects. Conversely Suppliers B and C are very voltage sensitive but not effected much by temperature.

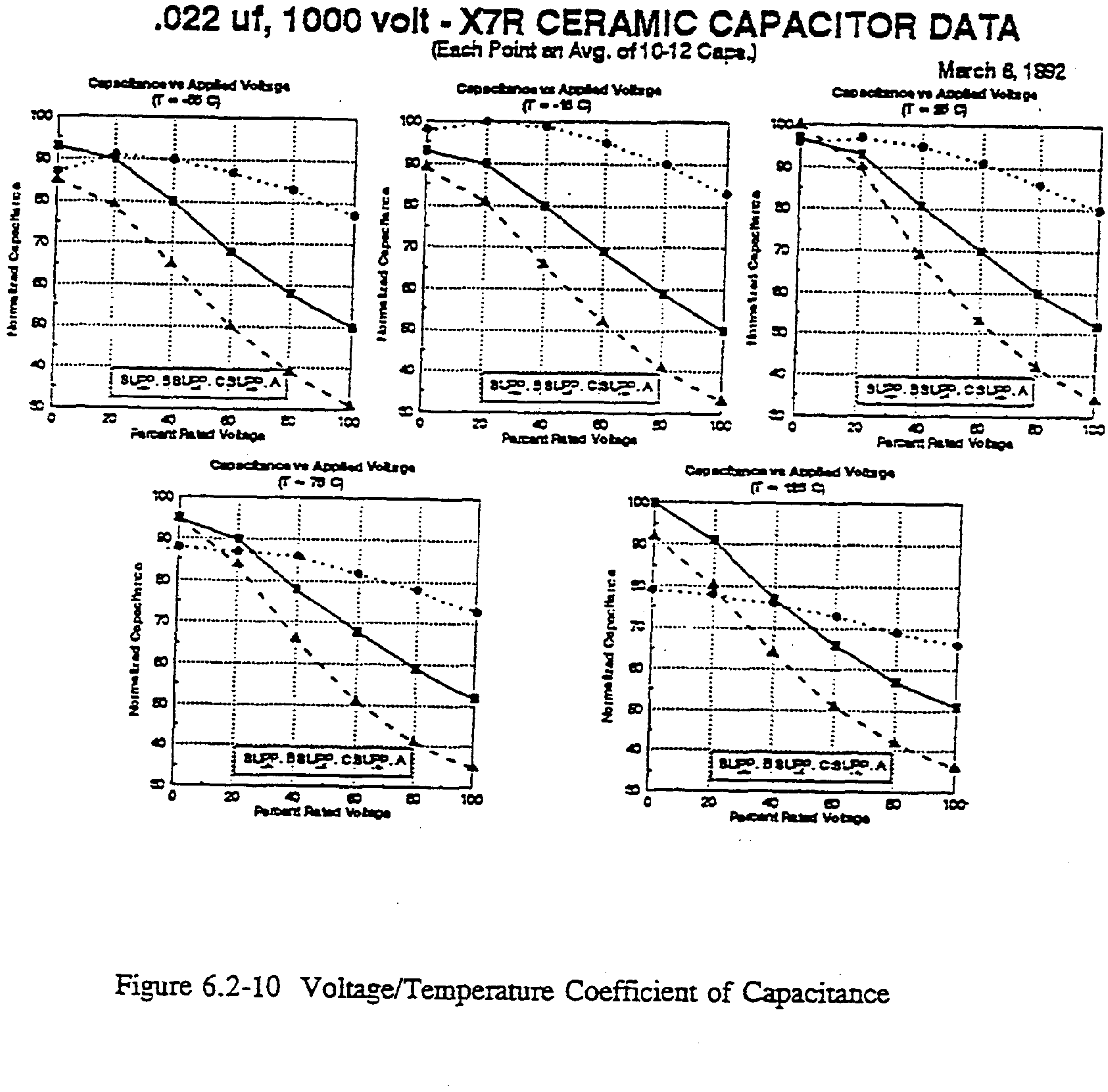


Figure 6.2-10 Voltage/Temperature Coefficient of Capacitance

Reasons for variations in voltage and temperature coefficients could be explained by inspecting Figures 6.2-11 and 6.2-12. These illustrations were the result of an exercise where parts from each supplier were sectioned so that electrode geometries and chemical constituents could be

measured. Figure 6.2-11, which shows the relative spacing of electrodes, reveals two points of interest. First, note two different constructions, Suppliers A and C use the floating electrode method while Supplier B uses the normal monolithic construction. It is obvious from inspection that voltage stresses between electrodes from Supplier C are greater than those from Supplier A. Since the voltage coefficient of capacitance is related to stress levels, the falloff of voltage part C should be worse then that of part A. In fact, Figure 6.2-10 shows this effect clearly. A finite element analysis of electric fields within the illustrated geometries shows that the monolithic structure will have approximately twice the electrode tip stresses as a comparably spaced floating electrode structure. This point is essentially a comparison of parts A and B and the voltage falloff curves support this, i.e. the parts have similar spacings but B will have higher stresses thus a faster falloff than A with voltage.

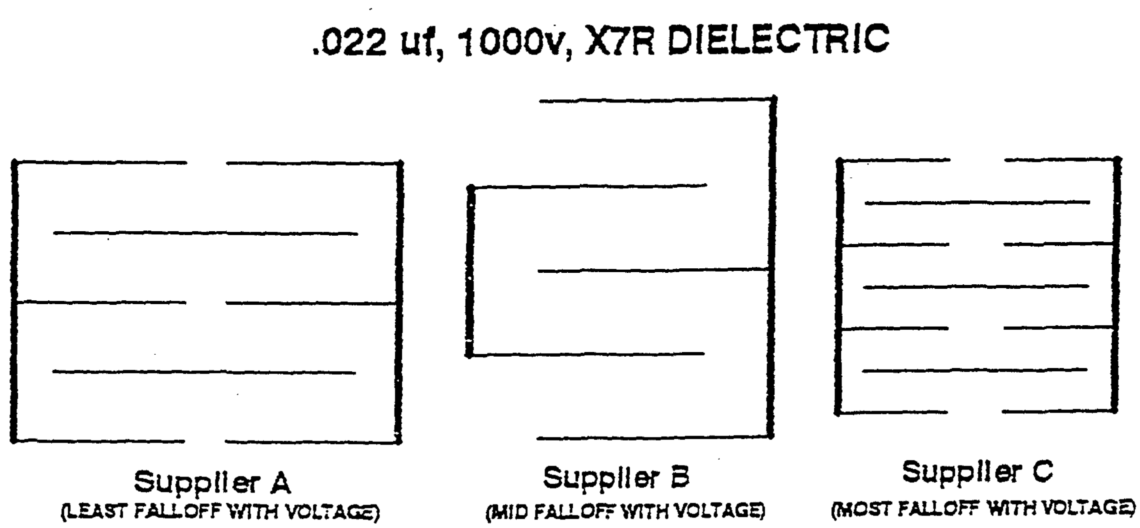


Figure 6.2-11 Relative Spacing (Stress)

Although there is no clear evidence, the evaluation of chemical constituents shown in Figure 6.2-12 may shed some light on why part A had a faster falloff with temperature than either parts B or C. Although the dielectric material constituents from all three parts vary, parts B and C seem more closely related than part A. In any case, even with all three parts specified as X7R dielectric, it can be seen that they do vary. Discussions with ceramic capacitor suppliers support the fact that most suppliers do some material customizing.

	Supplier A	Supplier B	Supplier C
Ba	43.6	48.0	51.0
Ti	20.4	21.0	22.1
O	21.0	23.2	22.9
Bi	7.8	5.5	0.4
Pb	3.7	1.7	1.1
Nb	1.6	0.6	0.9
V	1.3		1.0
Sr	0.7		
Zn			0.5

Weight Percent - Within 2%

Figure 6.2-12 Chemical Analysis (EDX) of X7R Capacitors

The environmental tests conducted on the test items are summarized in Figure 6.2-13. All details for conducting these tests are provided in Volume 3 of the Manufacturing Guidelines. Table 6.2-3 lists these procedures with reference section numbers from Volume 3.

TEST DESCRIPTION	TEST MEDIA	TEST RESULTS	COMMENTS
TEMPERATURE SHOCK	AIR	50 CYCLES IN SHUTTLE	-55 TO +95 C
CROW BAR	AIR	100 PULSES, RATED V	80 AMP PEAK
INRUSH CURRENT	AIR	100 PULSES, RATED V	65 AMPS PEAK
FLUID COMPATABILITY	FC 77	500 HOURS, STATIC	+100 C
RATED V LIFE TEST	MINERAL OIL	500 HRS, V APPLIED	-55 TO +100 C
1-1/2 V LIFE TEST	MINERAL OIL	1795 HRS, V APPLIED	-55 TO +100 C
CAP. VS TMP/VOLT	AIR	PLOTS	TO RATED V

Figure 6.2-13 Environmental Test Results

Para. No.	Description
1.1	Corona Test
1.2.1	Impedance Test
1.2.2	Leakage Current Test
1.2.3	Crow Bar Test
1.2.4	InRush Current Test
1.2.5	V & T Coefficients
1.2.6	Acoustical Tests

Table 6.2-3 Detailed Test Procedure Listing

Post test evaluations are also interesting. Figure 6.2-14 shows the results of a sampling of a group of 10-12 parts which had shown no defects from the SLAM evaluation during pre test characterizations. The post test SLAM tests show, for example, that parts from Supplier E were damaged by all tests while parts from Supplier C showed no ill effects. In addition the fluid compatibility and 1-1/2 rated applied voltage life tests appear to be especially damaging.

X7R TYPE DIELECTRIC - AFTER ENVIRONMENTAL TESTS

	.022 uf. 1000 V			2.2 uf. 500 V	
	Supplier B Damaged	Supplier C Damaged	Supplier A Damaged	Supplier D Damaged	Supplier E Damaged
Temp. Shock	0	0	0	1 of 10	2 of 11
Crow Bar/Inrush	0	0	0	0	1 of 10
Fluid Comp.	1 of 10	0	2 of 10	0	2 of 10
Full V Life	0	0	0	0	2 of 10
1-1/2 V Life	7 of 9	0	3 of 10	2 of 10	2 of 10
Cap. vs T & V	0	0	0	0	1. of 10

* Scanning Laser Acoustical Microscope

Sample Size Typically 10

Figure 6.2-14 Slam* Damage Assessment

The last item of interest of this ceramic capacitor effort concerns an attempt to show correlation between SLAM detected defects and corona characteristics. These results, shown inFigure 6.2-15, indicate very little trending and are not encouraging. Although the mean CIV of parts without defects is higher than those with known defects applying confidence factors of +/- three standard deviations yields an over lap of results. In addition, with 18 defected parts, 12 show no corona inception at the maximum applied voltage while only six do show inception at less than applied voltage. The tests were conducted per MIL-C-49467 with ac applied voltage of 0.7 percent vrms of the rated dc voltage or a peak voltage equal to the rated dc voltage.

CORONA INCEPTION VERSUS ACOUTSIC DEFECTS
(CIV @ 0.7 VAC per MIL-C-49467)

	Supplier B X7R, .022 UF	Supplier C X7R, .022 UF	Supplier A X7R, .022 UF
PARTS EXAMINED	97	97	100
WITH CORONA	96	74	4
WITH SLAM DEFECTS	7	0	11
DEFECTS W CORONA	6	0	0
DEFECTS W/O CORONA	1	0	11
W/O SLAM DEFECTS			
CIV AVG	556	694	658
CIV S.DEV	94	12	36
WITH SLAM DEFECTS			
CIV AVG	392		
CIV S.DEV	89		

Figure 6.2-15 Corona Correlation Effort

6.2.2.2 Mica

In order to establish standard methods of characterizing mica paper HV capacitors, we prepared designs for three "standard evaluation" HV mica paper capacitor types, for 3 kV, 5 kV, and 10 kV services, and obtained samples of these from five different manufacturers. We then characterized them in a number of different ways. The characterizations included:

Determining conformance to device requirements
Assessment tests intended to establish the relative rankings of various manufacturers products under selected operating conditions

Conformance to Requirements

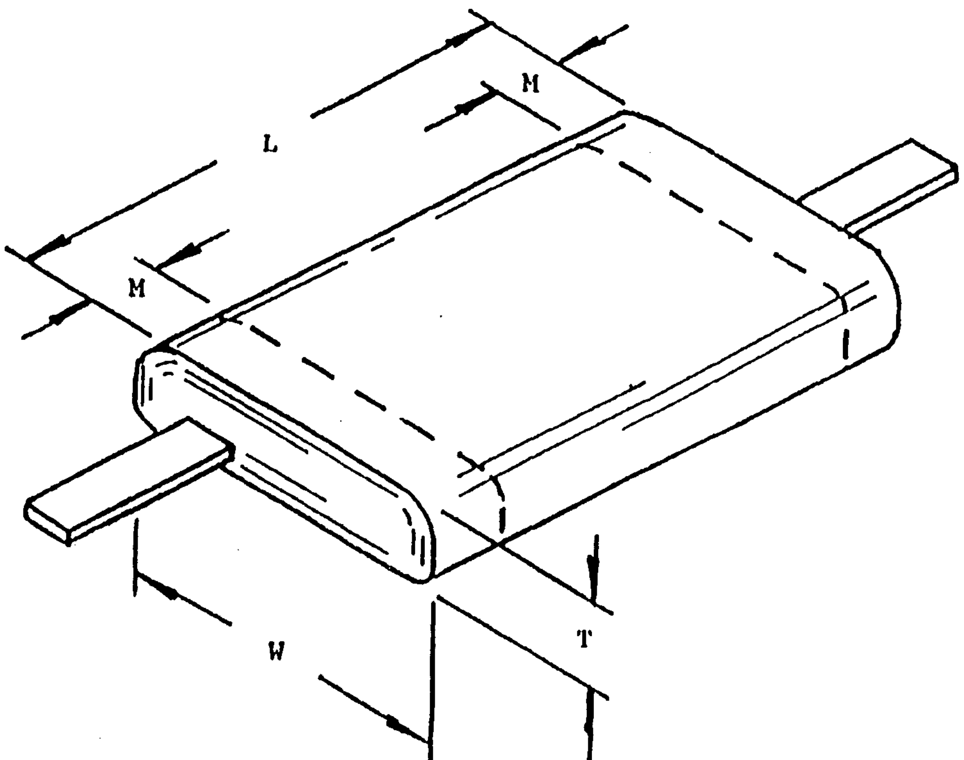
We used conventional analyses to determine if the capacitors fit within the physical envelope specified in the requirements document that we supplied to the manufacturers. We also determined whether or not the capacitance fell within the allowed range, and whether or not they withstood the specified DC voltage. Conventional methods were used for all of these characterizations.

The drawing against which we procured our capacitors for these studies is shown in Figure 6.2-16. Included in the figure is a table of specific dimensions, in inches, for the three capacitors types ordered. Conformance to physical size requirements was generally good, although 3 kV and 10 kV capacitors from Del, and 5 kV capacitors from Cera Mite did not meet all dimensional requirements. All capacitors conformed well to the requirement for capacitance, and most showed good dissipation factors.

Thermal Shock Tests

Thermal shock testing of the mica paper capacitors was performed to determine the effects of thermal stresses on the physical / mechanical integrities of the devices. Physical / mechanical integrity is a major determinant in the HV performance of a capacitor. To assess the effects of thermal stress, AC and DC corona measurements were made before and after exposure to thermal stress. Corona testing was chosen for this study because it is well known that changes in the capacitor's physical / mechanical characteristics will alter its corona discharge response. Six capacitors of each type were subjected to thermal shock cycling. The conditions used for thermal shock cycling are given in Table 6.2-4. Before and after the cycling each device was characterized using both AC and DC corona discharge, and were also subjected to DC dielectric withstanding voltage testing (DWV). The test voltages used in these characterizations are shown in Table 6.2-5. All high voltage testing was done in Freon TF at room temperature. These conditions eliminate discharge phenomena due to leads and external surface effects which can exist if testing is done in air or in inert gases at low pressures.

The results of the post thermal shock HV tests on the sample capacitors were quite good, and are indicative of generally good quality in the capacitors tested. In summary:



V_{RATING}	L	W	T (max)	M
3 KV	1.25	1.00	0.200	0.125
5 KV	1.50	1.00	0.200	0.200
10 KV	2.50	1.50	0.200	0.250

NOTES:

LEAD LENGTH — 1.0 INCH MIN
LEAD MATERIAL — Ni
LEAD FINISH — SOLDER COAT
END MARGINS (M) — SEE TABLE
IDENTIFY OUTER FOIL LEAD ●

Figure 6.2-16 Basic Mica Capacitor

PARAMETER	VALUE
Temp range	-55°C to 125°C
Transfer time	< 15 seconds
Dwell at temp. extremes	1.0 hours
No. of cycles	25

Table 6.2-4 Thermal shock conditions for the HV mica paper capacitors

Test Type	Capacitor Rating	Maximum Test Voltage
DC corona	3 kV	CIV or 4.5 kVDC
	5 kV	CIV or 7.5 kVDC
	10 kV	CIV or 13.5 kVDC
DC DWV	3 kV	4.5 kV
	5 kV	7.5 kV
	10 kV	13.5 kV
AC corona	3 kV	CIV or 3.0 kVAC
	5 kV	CIV or 5.0 kVAC
	10 kV	CIV or 10.0 kVAC

Table 6.2-5 Maximum test voltages employed in the HV testing of mica paper capacitors

Device Type	Sequence
3 kV - 22 nF	4.5 kV -> 4.5 kV -> 4.5 kV
5 kV - 15 nF	7.5 kV -> 7.5 kV -> 7.5 kV
10 kV - 10 nF	13.5 kV -> 13.5 kV -> 13.5 kV
Temperature (°C)	23 > 85 -> 125
Dwell time (hrs)	24 -> 100 -> 2000

Table 6.2-6 The three sequential sets of conditions used in the accelerated life testing of the HV mica paper capacitors

AC corona levels including both CIV and CEV values changed less than 20 percent for all of the capacitors tested, from all manufacturers.

DC corona levels were essentially unchanged for all devices from all manufacturers; no levels exceeded 20 picocoulombs per second before or after thermal shock.

No DWV failures occurred either before or after thermal shock for any device from any manufacturer.

Accelerated Life Testing.

Accelerated life testing is being performed to:

Within each device type (3 kV, 5 kV, and 10 kV), establish the relative operating life rankings for the products obtained from the five manufacturers.

Identify correlation's between device life times and their corona characteristics.

The life test conditions employed in these evaluations are outlined in Table 6.2-6. In these tests a total of 12 devices of each capacitor type from each manufacturer were evaluated. All devices placed on test first had to pass a 100 hour burning-in. Six of the 12 devices for each type were subjected to thermal shock cycling prior to testing. Also, prior to the start of these tests each device was subjected to AC and DC corona characterizations and to DC DWV testing After approximately 1100 hours of life testing, the parts were removed to confirm the observed failures, and to determine both the AC and DC corona characteristics of the devices that survived the life testing.

The failures were confirmed by subjecting the capacitors that appeared to have failed to a 20 second DWV test at its appropriate life test voltage. Devices failing these tests were considered life test failures. Based on these results a summary of the life test failures occurring during the 1100 hours of testing is given in Table 6.2-7.

The DC corona characterization included three different measurement conditions:

A thirty second charge accumulation period at the device's rated voltage. All of the devices to be tested were treated in this way.

A five minute charge accumulation period at the device's life test voltage. All of the devices to be tested were treated in this way.

A 20 minute charge accumulation period at the device's life test voltage. Within each part type, two capacitors from each manufacturer were subjected to this test - the capacitor that produced the highest corona response, and the capacitor that produced the lowest corona response.

The objectives of these DC corona measurements are to observe if the ranking of the capacitor corona response changes when the measurement time and voltage is changed, and to determine which measurement condition more accurately reflects device quality as

Device Type	Manufacturer	Number of Failures
3 kV - 22 nF	Cera-Mite	0 (11)
	Custom	1 (12)
	Del	3 (10)
	Reynolds	0 (12)
	Tobe Deutschman	1 (11)
5 kV - 15 nF	Cera-Mite	0 (12)
	Custom	0 (12)
10 kV - 10 nF	Cera-Mite	0 (04*)
	Custom	0 (12)
	Del	9 (09)
	Reynolds	1 (12)
	Tobe Deutschman	0 (12)

Table 6.2-7 Confirmed failures occurring during the initial 1100 hours of accelerated life testing of the HV mica paper capacitors

( ) - denotes number devices starting test
* - 8 units not started due to equipment capacity

determined by the number of failures observed during the life testing. The reason that we wished to consider several different DC corona discharge conditions is that DC corona discharge is a process that may occur somewhat randomly in time. Therefore, it is difficult to predict in advance, the best set of test conditions for a given type of capacitor.

Upon completion of the DC corona determinations, all unfailed devices were returned to life tests to complete the 2000 hours test period. At that time those devices that did not fail were electrically characterized.

The complete set of data obtained in these studies are shown in Table 6.2-9 through 6.2-20. Table 6.2-8 correlates the information in these tables with the capacitor manufacturer and the voltage of the capacitors.

Table Number	Manufacturer	Voltage Rating (kV)
9	Cera-Mite	3
10	Custom	3
11	Del	3
12	Reynolds	3
13	Tobe Deutschman	3
14	Cera-Mite	5
15	Custom	5
16	Cera-Mite	10
17	Custom	10
18	Del	10
19	Reynolds	10
20	Tobe Deutschman	10

Table 6.2.8 Capacitors for which test results appear in Tables 6.2-9 through 20

Data appears in the following tables for each of the 12 capacitors that were studied. In these tables we report the measured capacitance in nanoFarads, the dissipation factor (DF), the insulation resistance measured at different times after the application of 500 VDC, AC corona behavior when immersed in Freon TF , including corona inception voltage (CIV) and corona extinction voltage (CEV), the capacitor's measured dimensions in inches, DC corona behavior measured at 1.5 times the capacitor's voltage rating for the indicated periods of time, and dielectric withstanding voltage (DWF).

The following is a cross reference guide to specific program details, procedural details and reference information in Volumes 2, 3, and 4 respectively that relate to ceramic and/or mica capacitors.

Volume 2 Program Details

Section 3.0 Test Parameter of Components

This section lists key parameters for various components used in HVPS. Included are type of test, data taken, test method, and purpose of test.

Volume 3 Procedural Details

Section 1.2 Capacitors

This section contains a summary of mica and ceramic capacitor testing and general conclusions.

Section 1.2.1 Impedence Measurement Test Procedure

This section contains procedure for impedance testing, a sketch of the adapter for HP4192A impedance analyzer and a listing of computer programs to conduct impedance measurements.

Section 1.2.2 Leakage Current Measurement Test Procedure

This section contains the procedures for leakage measurement, a sketch of the test arrangement, a drawing of the test fixture design, and the computer program to conduct leakage measurements.

Section 1.2.3 Crowbar Test Procedure

This section contains the procedure for capacitor crowbar test, the test setup, and the design of the test fixture.

Section 1.2.4 Inrush Current Test Procedure

This section contains the inrush current test procedure, the test setup, and the test fixture design.

Section 1.2.5 Voltage Coefficient and Temperature Coefficient Test Procedure

This section contains the voltage and temperature coefficient test procedure, the test setup, and the test fixture design.

Section 1.2.6 Acoustic Evaluation

This section contains information on Sonoscan's SLAM and C-SAM equipment which was used for acoustic evaluation.

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	22.93	23.69	23.26	22.02	23.47	22.76	22.83	23.15	23.34	22.38	22.08	22.87
df	0.0036	0.0034	0.0036	0.0035	0.0036	0.0035	0.0035	0.0036	0.0034	0.0034	0.0036	0.0035
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	2.00	1.92	1.96	1.92	2.05	2.03	2.07	2.08	2.09	2.01	1.96	2.08
@ 60 secs	1.09	1.05	1.13	1.07	1.12	1.11	1.09	1.12	1.13	1.06	1.06	1.11
@ 120 secs	0.61	0.582	0.628	0.599	0.648	0.621	0.616	0.638	0.629	0.605	0.592	0.612
Freon corona ac												
civ	490	640	600	520	500	590	490	770	700	730	690	490
cev	320	480	370	340	310	320	320	490	480	510	510	320
dimensions												
length	1.30	1.29	1.30	1.29	1.29							
width	0.963	0.972	0.978	0.98	0.976							
thickness	0.116	0.116	0.115	0.115	0.115							
width of foil	0.90	0.90	0.90	0.921	0.909							
end margin	.190/.200	.182/.200	.200/.200	.177/.200	.190/.200							

Cera Mite -3
Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	22.92	23.68	23.26	22.03	23.47	22.76	22.82	23.14	23.34	22.38	22.08	22.86
df low	0.0037	0.0036	0.0038	0.0037	0.0038	0.0037	0.0037	0.0038	0.0036	0.0036	0.0038	0.0036
df high	0.0038	0.0037	0.0038	0.0038	0.0039	0.0038	0.0038	0.0038	0.0036	0.0037	0.0039	0.0038
ir @ 500 vdc												
leakage current	na											
@ 30 sec	2.07	2.16	2.17	2.11	2.17	2.26	2.14	2.25	2.25	2.16	2.13	2.23
@ 60 sec	1.16	1.19	1.21	1.14	1.21	1.25	1.19	1.26	1.26	1.22	1.16	1.21
@ 120 sec	0.641	0.667	0.597	0.66	0.696	0.702	0.671	0.698	0.708	0.693	0.654	0.676
corona ac volts (freon)												
civ	530	780	540	560	fail	680	540	790	630	780	780	480
cev	420	450	430	460	*	540	400	620	500	540	630	400
corona dc volts (freon) @ 4.5 v												
10 sec ct	0	0	0	0	fail	0	0	0	0	0	0	0
dwv @ 4.5 kv												
20 sec ct	pass	pass	pass	pass	*	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	510	*	*	520	*	500	*	670	*	740	*	510
cev	430	*	*	400	*	420	*	600	*	620	*	430
corona dc volts (freon) @ 4.5k volts												
10 secs ct	0	*	*	1.00	*	1.00	*	0.50	*	0.20	*	0.50
dwv @ 4.5 kvdc 20 secs												
pass/fail	pass	*	*	pass	*	pass	*	pass	*	pass	*	pass

Cera Mite -3
Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	560	620	610	530	*	560	600	560	600	730	640	540
cev	420	480	480	410	*	460	500	430	500	580	540	420
corona dc volts (freon)												
@ 3.0kvdc 30sec	0.83	0	0	0.83	*	0.23	0.06	0.06	0.16	0	0	0
@ 4.5kvdc 5min	2.40	4.40	6.60	7.20	*	5.40	14.20	7.20	21.50	2.80	2.00	4.00
@ 4.5 kvdc 20mn												

Table 6.2-9 Cera-Mite 1 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	23.40	23.61	23.41	22.46	23.24	23.00	23.68	23.64	22.74	23.46	23.54	22.44
df	0.0016	0.0016	0.0016	0.0017	0.0016	0.0016	0.0016	0.0016	0.0017	0.0016	0.0016	0.0017
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	4.07	3.61	3.87	3.65	3.68	3.65	3.72	4.04	4.13	3.71	3.97	3.98
@ 60 secs	2.20	2.01	2.10	2.02	1.99	2.02	2.04	2.17	2.23	1.99	2.20	2.13
@ 120 secs	1.20	1.11	1.14	1.11	1.10	1.10	1.12	1.17	1.22	1.10	1.16	1.15
Freon corona ac												
civ	1130	1130	1250	1030	1330	1350	1140	1080	1090	1400	1320	1230
cev	900	800	810	690	810	1000	810	550	680	970	820	690
dimensions												
length	1.14	1.14	1.16	1.16	1.14							
width	0.922	0.929	0.925	0.92	0.933							
thickness	0.107	0.107	0.107	0.108	0.106							
width of foil	0.765	0.77	0.765	0.77	0.763							
end margin	.180/.200	.180/.200	.184/.200	.184/.200	.184/.195							

Custom -3
Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	23.34	23.55	23.35	22.42	23.18	22.93	23.62	23.59	22.69	23.42	23.48	22.40
df low	0.0016	0.0016	0.0016	0.0017	0.0016	0.0016	0.0016	0.0016	0.0017	0.0016	0.0016	0.0017
df high	0.0016	0.0016	0.0016	0.0018	0.0016	0.0016	0.0016	0.0016	0.0018	0.0016	0.0016	0.0018
ir @ 500 vdc												
leakage current	na											
@ 30 sec	3.15	3.23	3.19	2.94	3.10	3.09	3.07	3.27	4.25	3.84	4.11	4.02
@ 60 sec	1.84	1.79	1.82	1.74	1.79	1.80	1.77	1.79	2.20	2.03	2.20	2.09
@ 120 sec	1.04	1.02	1.08	1.00	1.03	1.02	1.04	1.05	1.21	1.09	1.17	1.12
corona ac volts (freon)												
civ	1020	1040	940	940	940	1170	1080	820	780	910	720	980
cev	690	820	810	830	670	890	910	420	650	700	630	800
corona dc volts (freon) @ 4.5 v												
10 sec ct	0	0	0	0	0	0	0	0	0	0	0	0
dwv @ 4.5 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	730	•	940	•	740	•	1070	•	710	•	750	•
cev	550	•	830	•	640	•	920	•	600	•	620	•
corona dc volts (freon) @ 4.5k volts												
10 secs ct	1.00	•	0	•	0	•	0	•	0	•	0	•
dwv @ 4.5 kvdc 20 secs												
pass/fail	pass	•	pass	•	pass	•	pass	•	pass	•	pass	•

Custom -3
Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	570	560	580	610	610	540	560	570	•	530	450	620
cev	490	470	490	510	520	460	480	500	•	430	380	480
corona dc volts (freon)												
@ 3.0kvdc 30sec	0.17	0	0	0.07	0	0.33	0.07	0.07	•	0.33	0	0.17
@ 4.5kvdc 5min	5.00	0.40	11.20	5.60	0.40	4.00	4.40	12.80	•	1.00	3.40	2.00
@ 4.5 kvdc 20mn												

Table 6.2-10 Custom 1 Capacitor Characterization

Del -3

AS RECEIVED

Serial No.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	20.94	22.36	22.96	20.87	21.08	21.40	22.19	21.19	21.64	21.92	21.32	21.21
DF	0.0076	0.0072	0.008	0.0078	0.0082	0.0082	0.0077	0.0076	0.0069	0.0072	0.0075	0.009
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	9.27	11.60	13.80	8.27	10.00	14.20	9.94	9.61	8.50	7.69	8.70	15.72
@ 60 secs	5.99	7.81	9.39	5.23	6.50	10.20	6.31	6.09	5.26	4.66	5.42	10.58
@ 120 secs	3.98	5.65	6.78	3.35	4.51	7.85	4.18	4.02	3.37	3.00	3.59	7.60
Freon corona ac												
civ	520	410	470	530	520	510	810	520	500	540	580	510
cev	410	370	300	340	360	330	520	340	370	320	340	330
dimensions												
length	1.31	1.34	1.34	1.33	1.30							
width	0.961	0.978	0.978	0.968	0.972							
thickness	0.115	0.116	0.116	0.119	0.116							
width of foil	1.02	1.02	1.04	1.02	1.02							
end margin	.130/130	.130/.130	.123/.141	.139/139	.140/.140							

Del -3

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	20.68	21.98	22.43	20.44	20.80	20.78	21.60	20.86	21.56	21.74	21.04	20.63
df	0.006	0.0056	0.0062	0.006	0.0069	0.006	0.0058	0.0063	0.0062	0.0062	0.0064	0.0062
ir @ 500 vdc												
leakage current	na											
@ 30 sec	8.83	8.15	10.80	8.16	9.91	8.59	8.89	8.72	60.00	99	9.05	7.41
@ 60 sec	5.04	4.72	6.6	4.86	5.95	5.07	5.24	5.21	60/100	59	5.32	4.38
@ 120 sec	3.15	2.91	4.1	2.98	3.74	3.09	3.2	3.2	30/100	34	3.26	2.73
corona ac volts (freon)												
civ	360	400	410	360	430	380	390	320	430	400	380	340
cev	300	330	380	270	370	320	300	270	330	340	300	260
corona dc volts												
(freon) @ 4.5 v									fail @			
10 sec ct	0	0	0	0	0	0	0	0	1.86k	0	0	0
dwv @ 4.5 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	400	•	430	•	430	•	410	•	•	•	390	•
cev	350	•	380	•	370	•	360	•	•	•	320	•
corona dc volts												
(freon)												
@ 4.5k volts												
10 secs ct	0.20	•	0	•	0	•	0.20	•	•	•	0.20	•
dwv @ 4.5 kvdc												
20 secs												
pass/fail	pass		pass		pass		pass				pass	

Del -3

Post Life Test 670 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon)												
civ	•	•	410.00	390.00	420.00	370.00	380.00	•	•	•	390.00	410.00
cev	•	•	340.00	250.00	330.00	310.00	300.00	•	•	•	300.00	280.00
corona dc volts												
(freon)												
@ 3.0kvdc 30sec	•	•	0.00	0.00	0.00	0.17	0.40	•	•	•	0.57	0.00
@ 4.5kvdc 5min	•	•	9.40	4.80	9.20	13.80	2.20	•	•	•	0.40	8.60
@ 4.5 kvdc 20mn	•	•				6.95	10.20	•	•	•		

Table 6.2-11 Del 1 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	21.80	21.82	23.16	21.76	23.23	23.46	21.82	22.15	21.19	22.21	22.73	21.68
DF	0.0025	0.0026	0.0024	0.0024	0.0023	0.0022	0.0022	0.0024	0.0024	0.0024	0.0022	0.0025
ir @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	4.39	4.29	4.45	4.56	4.59	4.53	4.22	4.41	4.60	4.61	4.73	4.41
@ 60 secs	2.35	2.32	2.44	2.47	2.47	2.49	2.31	2.31	2.44	2.45	2.45	2.33
@ 120 secs	1.28	1.26	1.32	1.32	1.30	1.31	1.29	1.23	1.32	1.32	1.33	1.28
Freon corona ac												
civ	1.25k	890	1.16k	840	1.06k	1.05k	1.45k	880	1.09k	1.14k	1.16k	900
cev	770	650	830	740	830	820	1.09k	610	600	870	850	720
dimensions												
length	1.18	1.20	1.19	1.20	1.18							
width	0.938	0.945	0.942	0.936	0.94							
thickness	0.121	0.121	0.12	0.122	0.121							
width of foil	0.925	0.90	0.893	0.90	0.903							
end margin	.127/.136	.136/.136	.128/.158	.135/.160	.140/.150							

Reynolds -3

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	21.66	21.69	22.98	21.62	23.04	23.28	21.71	22.02	21.07	22.17	22.59	21.56
df low	0.0017	0.0017	0.0015	0.0016	0.0014	0.0014	0.0016	0.0016	0.0017	0.0015	0.0015	0.0017
df high	0.0017	0.0017	0.0015	0.0016	0.0015	0.0014	0.0017	0.0017	0.0018	0.0016	0.0016	0.0018
ir @ 500 vdc												
leakage current	na											
@ 30 sec	3.74	3.79	3.91	3.86	3.79	3.83	3.43	3.67	3.89	3.88	3.86	3.61
@ 60 sec	2.02	1.97	2.12	2.08	2.07	2.07	1.77	1.93	2.00	2.04	2.03	1.91
@ 120 sec	1.07	1.07	1.12	1.12	1.14	1.14	0.94	1.05	1.08	1.12	1.13	1.04
corona ac volts (freon)												
civ	930	920	720	850	770	620	1.11k	720	970	900	970	1.0k
cev	840	800	630	680	660	520	970	600	830	650	730	830
corona dc volts (freon) @ 4.5 v												
10 sec ct	0	0	0	0	0	0	0	0	0	0	0	0
dwv @ 4.5 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	900	820	•	810	•	•	•	700	770	•	•	850
cev	760	650	•	630	•	•	•	620	640	•	•	730
corona dc volts (freon) @ 4.5k volts												
10 secs ct	0.50	0	•	0	•	•	•	0.20	0.20	•	•	0.50
dwv @ 4.5 kvdc 20 secs												
pass/fail	pass	pass	•	pass	•	•	•	pass	pass	•	•	pass

Reynolds -3

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	740	750	510	690	650	450	840	630	800	590	600	700
cev	400	470	370	470	470	350	570	480	390	450	450	440
corona dc volts (freon)												
@ 3.0kvdc 30sec	0.00	0.00	0.00	0.33	0.00	0.50	0.00	0.07	0.00	0.07	0.90	0.00
@ 4.5kvdc 5min	4.20	19.80	0.40	0.40	19.40	1.40	18.00	0.00	2.80	4.60	4.80	5.40
@ 4.5 kvdc 20mn												

Table 6.2-12 Reynolds 1 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	22.15	22.75	22.89	21.65	23.34	22.83	23.16	23.46	22.02	23.90	21.66	23.19
DF	0.0027	0.0028	0.0027	0.0028	0.0027	0.0026	0.0026	0.0026	0.0028	0.0026	0.0029	0.0026
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.83	1.88	1.92	1.90	2.05	2.00	2.00	2.11	1.89	2.13	1.94	2.04
@ 60 secs	1.05	1.03	1.07	1.02	1.12	1.09	1.10	1.14	1.04	1.16	1.04	1.11
@ 120 secs	0.567	0.593	0.592	0.561	0.622	0.60	0.619	0.631	0.583	0.632	0.568	0.613
Freon corona ac												
civ	980	1.35k	1.54k	1.27k	1.16k	1.36k	1.17k	970	920	1.63k	1.08k	920
cev	880	840	1.00k	900	820	840	750	640	700	1.14k	740	710
dimensions												
length	1.32	1.32	1.32	1.32	1.32							
width	0.864	0.856	0.854	0.86	0.862							
thickness	0.121	0.118	0.117	0.121	0.116							
width of foil	1.02	1.08	1.01	1.02	1.01							
end margin	.136/.162	.160/.160	.133/.172	.141/.166	.164/.164							

Tobe D -3

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	22.08	22.68	22.8	21.58	23.38	22.75	23.08	23.36	21.94	23.82	21.57	23.10
df low	0.0023	0.0023	0.0023	0.0024	0.0031	0.0022	0.0022	0.0022	0.0024	0.0022	0.0024	0.0022
df high	0.0024	0.0024	0.0024	0.0024	0.0031	0.0023	0.0022	0.0022	0.0024	0.0022	0.0024	0.0022
ir @ 500 vdc												
leakage current	na											
@ 30 sec	1.87	1.90	1.88	1.80	2.35	2.01	2.03	1.97	1.75	2.06	1.81	1.95
@ 60 sec	1.02	1.03	1.02	0.99	1.28	1.07	1.1	1.08	0.97	1.11	0.99	1.06
@ 120 sec	0.57	0.57	0.58	0.55	0.72	0.59	0.62	0.6	0.53	0.61	0.54	0.59
corona ac volts												
(freon)												
civ	850	850	1.03k	770	880	810	910	620	850	960	820	810
cev	760	780	930	620	780	670	780	550	740	710	670	720
corona dc volts												
(freon) @ 4.5 v					fail @							
10 sec ct	0	0	0	2.50	2.8k	0	0	0	0	0	0	0
dwv @ 4.5 kv												
20 sec ct	pass	pass	pass	pass	*	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	840	*	1.0k	*	*	820	*	640	850	*	*	770
cev	760	*	940	*	*	710	*	550	720	*	*	710
corona dc volts												
(freon)												
@ 4.5k volts												
10 secs ct	0.50	*	0.50	*	*	0	*	0.00	2.50	*	*	0.20
dwv @ 4.5 kvdc												
20 secs												
pass/fail	pass	*	pass	*	*	pass	*	pass	pass	*	*	pass

Tobe D -3

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon)												
civ	640	630	650	*	*	590	640	650	600	590	580	610
cev	540	500	580	*	*	470	530	530	530	490	500	520
corona dc volts												
(freon)												
@ 3.0kvdc 30sec	0.00	0.00	0.07	*	*	0.17	0.00	0.17	0.07	0.00	0.07	0.33
@ 4.5kvdc 5min	2.20	0.00	3.40	*	*	9.00	0.00	0.40	0.40	4.40	0.00	1.00
@ 4.5 kvdc 20mn												

Table 6.2-13 Tobe Deutschman 1 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	15.14	15.14	15.01	14.92	15.48	14.88	14.78	14.82	14.72	14.67	14.91	15.05
df	0.0044	0.0046	0.0044	0.0046	0.0042	0.0046	0.0045	0.0046	0.0046	0.0045	0.0045	0.0045
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.14	1.17	1.17	1.10	1.20	1.19	1.14	1.11	1.16	1.17	1.18	1.16
@ 60 secs	0.61	0.64	0.65	0.59	0.67	0.64	0.62	0.62	0.62	0.61	0.62	0.64
@ 120 secs	0.333	0.348	0.344	0.335	0.362	0.352	0.34	0.338	0.338	0.331	0.334	0.342
Freon corona ac												
civ	540	530	550	590	530	560	560	480	610	530	520	530
cev	430	430	440	490	460	460	430	420	440	420	460	400
dimensions												
length	1.54	1.55	1.56	1.56	1.56							
width	1.054	1.055	1.056	1.062	1.061							
thickness	0.182	0.18	0.185	0.186	0.177							
width of foil	1.08	1.08	1.08	1.07	1.08							
end margin	.219/.261	.235/.253	.215/.247	.237/.258	.195/.277							

Cera Mite -5

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	15.12	15.14	14.99	14.91	15.46	14.86	14.78	14.81	14.72	14.66	14.9	15.04
df	0.0046	0.0048	0.0045	0.0046	0.0042	0.0046	0.0046	0.0047	0.0048	0.0046	0.0046	0.0046
ir @ 500 vdc												
leakage current	na											
@ 30 sec	1.17	1.21	1.25	1.16	1.28	1.25	1.19	1.24	1.25	1.22	1.25	1.24
@ 60 sec	0.61	0.64	0.65	0.63	0.69	0.66	0.65	0.67	0.66	0.64	0.67	0.65
@ 120 sec	0.33	0.36	0.36	0.34	0.38	0.37	0.36	0.38	0.36	0.36	0.37	0.36
corona ac volts (freon)												
civ	550	500	500	570	500	530	520	520	570	550	520	510
cev	400	380	430	490	470	460	450	460	500	460	440	430
corona dc volts (freon) @ 7.5 Kv												
10 sec ct	0	0.20	0.20	0	0.50	0.20	1.40	0.40	0	0	0.20	0
dwv @ 7.5 kv												
20 sec ct	pass	pass	pass	pass	•	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	590	•	530	•	550	•	570	•	600	•	540	•
cev	470	•	420	•	450	•	470	•	500	•	440	•
corona dc volts (freon) @ 7.5k volts												
10 secs ct	0.40	•	0.60	•	0.70	•	1.00	•	0.60	•	0.20	•
dwv @ 7.5 kvdc 20 secs												
pass/fail	pass	•	pass	•	pass	•	pass	•	pass	•	pass	•

Cera Mite -5

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	650	590	560	580	600	570	610	580	600	580	620	580
cev	500	510	450	490	470	480	530	460	510	460	510	480
corona dc volts (freon)												
@ 5.0kvdc 30sec	0.13	0.13	0.40	0.00	0.33	0.20	0.06	0.00	0.06	0	0.16	0.43
@ 7.5kvdc 5mn	9.00	10.20	5.40	6.40	35.80	21.00	14.60	19.80	3.00	8.20	21.00	34.80
@ 7.5kvdc 20mn												

Table 6.2-14 Cera-Mite 2 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	14.42	14.46	14.53	14.34	14.75	14.66	14.95	14.78	14.50	14.60	14.36	14.38
df.	0.002	0.0021	0.0021	0.0021	0.002	0.0021	0.0021	0.0021	0.002	0.0021	0.0022	0.0022
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.52	1.54	1.48	1.52	1.53	1.51	1.54	1.55	1.55	1.57	1.65	1.50
@ 60 secs	0.85	0.87	0.82	0.86	0.87	0.86	0.86	0.87	0.86	0.89	0.93	0.85
@ 120 secs	0.48	0.5	0.46	0.49	0.48	0.48	0.49	0.50	0.48	0.51	0.52	0.48
Freon corona ac												
civ	720	1260	1140	1000	1150	1340	1180	1350	970	1200	960	1230
cev	590	1080	980	780	870	930	1000	1190	840	970	830	990
dimensions												
length	1.43	1.41	1.43	1.42	1.41							
width	0.84	0.86	0.83	0.84	0.87							
thickness	0.19	0.19	0.19	0.19	0.19							
width of foil	0.89	0.89	0.89	0.89	0.89							
end margin	.260/.290	.235/.290	.282/.282	.234/.290	.254/.290							

Custom -5

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	14.38	14.41	14.49	14.29	14.71	14.61	14.91	14.73	14.46	14.55	14.31	14.34
df	0.0021	0.0021	0.0021	0.0021	0.002	0.0021	0.0021	0.0021	0.002	0.0021	0.0021	0.0021
ir @ 500 vdc												
leakage current	na											
@ 30 sec	1.70	1.77	1.60	1.78	1.73	1.5	1.72	1.76	1.70	1.78	1.84	1.69
@ 60 sec	0.94	1.01	0.90	1.01	0.97	0.90	0.96	0.98	0.97	1.04	1.05	0.95
@ 120 sec	0.55	0.59	0.52	0.59	0.56	0.54	0.56	0.57	0.55	0.60	0.60	0.55
corona ac volts (freon)												
civ	760	1060	860	980	1100	1130	900	930	990	950	950	800
cev	570	900	690	830	950	880	810	800	840	680	760	680
corona dc volts (freon) @ 7.5 Kv												
10 sec ct	0	0.20	0	0	0	0	0	0	0	0	0.20	0
dwv @ 7.5 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	700	•	950	•	1000	•	670	•	970	•	•	900
cev	560	•	840	•	830	•	540	•	640	•	•	620
corona dc volts (freon)												
@ 7.5k volts												
10 secs ct	0.20	•	0.20	•	0.50	•	0.90	•	0.50	•	•	1.00
dwv @ 7.5 kvdc 20 secs												
pass/fail	pass	•	pass	•	pass	•	pass	•	pass	•	•	pass

Custom -5

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	710	740	790	690	650	770	630	750	600	750	750	730
cev	600	630	660	540	540	670	530	660	460	610	610	590
corona dc volts (freon)												
@ 5.0kvdc 30sec	0.30	0.07	0.00	0.23	0.07	0.00	0.07	0.17	0.07	0.50	0.07	0.40
@ 7.5kvdc 5mn	4.60	18.80	6.00	5.60	2.00	5.80	1.60	18.80	1.20	3.40	10.80	10.60
@ 7.5kvdc 20mn												

Table 6.2-15 Custom 2 Capacitor Characterization

AS RECEIVED Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	10.45	10.89	10.34	10.10	10.59	10.25	10.70	10.43	10.52	10.54	10.18	10.32
df	0.0045	0.0043	0.0046	0.0047	0.0045	0.0046	0.0045	0.0045	0.0046	0.0045	0.0047	0.0046
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	0.75	0.74	0.73	0.68	0.75	0.73	0.78	0.73	0.71	0.77	0.70	0.75
@ 60 secs	0.35	0.35	0.41	0.37	0.43	0.41	0.41	0.38	0.41	0.41	0.40	0.38
@ 120 secs	0.15	0.20	0.22	0.21	0.25	0.22	0.24	0.21	0.23	0.24	0.23	0.23
	0.35	0.38										
Freon corona ac												
civ	1170	1130	1420	1170	1150	1100	1150	1360	1210	1510	1100	1350
cev	940	940	1080	900	920	870	940	1090	950	1120	810	1070
dimensions												
length	2.52	2.52	2.53	2.54	2.52							
width	1.46	1.45	1.46	1.46	1.46							
thickness	0.17	0.17	0.18	0.17	0.18							
width of foil	1.64	1.65	1.63	1.65	1.64							
end margin	.425/.460	.425/.463	.438/.460	.425/.468	.432/.465							

Cera mite -10

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	10.44	10.88	10.33	10.09	10.57	10.24	10.69	10.43	10.51	10.53	10.18	10.32
df	0.0047	0.0045	0.0048	0.0049	0.0046	0.0048	0.0046	0.0047	0.0047	0.0046	0.0048	0.0047
ir @ 500 vdc												
leakage current	na											
@ 30 sec	0.81	0.91	0.80	0.77	0.84	0.80	0.82	0.61	0.83	0.79	0.80	0.79
@ 60 sec	0.42	0.49	0.44	0.42	0.46	0.44	0.45	0.44	0.45	0.43	0.43	0.45
@ 120 sec	0.24	0.28	0.25	0.24	0.27	0.25	0.26	0.23	0.26	0.25	0.25	0.25
corona ac volts (freon)												
civ	1140	1150	1320	1170	1200	1100	1100	1470	1180	1360	1190	1230
cev	860	930	1060	990	970	940	890	1150	950	1100	980	980
corona dc volts (freon) @ 13.0 kv												
10 sec ct	0	0.70	0	0	0.20	0.20	0	0	0	0	0	0
dwv @ 14.0 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	1170	•	1230	•	1350	•	1160	•	1190	•	1160	•
cev	970	•	990	•	1210	•	940	•	1000	•	960	•
corona dc volts (freon) @ 13.0k volts												
10 secs ct	1.60	•	1.00	•	0.70	•	0.70	•	0.50	•	0.20	•
dwv @ kvdc 20 secs												
pass/fail	pass	•	pass	•	pass	•	pass	•	pass	•	pass	•

Cera mite -10

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	1460	1470	1530	1540								
cev	1080	1220	1210	1390								
corona dc volts (freon)												
@10.0kvdc 30sc	0.17	0.07	0.20	0.40								
@ 13.5kvdc 5mn	15.60	21.60	19.00	29.60								
@13.5kvdc 20mn		3.60		3.85								

Table 6.2-16 Cera-Mite 3 Capacitor Characterization

Custom K-10

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	9.68	9.70	9.82	9.46	9.98	10.23	9.87	10.07	9.78	10.19	9.98	9.77
df	0.002	0.0021	0.0021	0.0021	0.002	0.0019	0.002	0.002	0.002	0.0019	0.002	0.0021
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	0.84	0.82	0.83	0.78	0.84	0.88	0.84	0.84	0.81	0.88	0.84	0.81
@ 60 secs	0.45	0.45	0.45	0.44	0.44	0.45	0.47	0.47	0.46	0.48	0.46	0.46
@ 120 secs	0.26	0.26	0.25	0.24	0.27	0.28	0.26	0.27	0.26	0.27	0.26	0.26
Freon corona ac												
civ	2330	2230	2320	2180	1960	2210	2060	1980	2320	2240	2290	2470
cev	1410	1700	2110	1850	1600	1980	1720	1720	1440	2040	1930	1940
dimensions												
length	2.42	2.42	2.42	2.42	2.42							
width	1.37	1.38	1.38	1.38	1.38							
thickness	0.17	0.17	0.17	0.17	0.16							
width of foil	1.66	1.65	1.64	1.63	1.63							
end margin	.377/.406	.379/.401	.373/.423	.383/.410	.380/.422							

Custom -10
Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	9.66	9.68	9.80	9.44	9.95	10.21	9.85	10.05	9.76	10.16	9.96	9.74
df	0.002	0.0021	0.0021	0.0021	0.002	0.0019	0.002	0.002	0.0021	0.0019	0.002	0.0021
ir @ 500 vdc												
leakage current	na											
@ 30 sec	0.79	0.78	0.76	0.74	0.81	0.85	0.81	0.83	0.80	0.83	0.82	0.79
@ 60 sec	0.41	0.43	0.42	0.41	0.43	0.47	0.45	0.45	0.43	0.47	0.44	0.43
@ 120 sec	0.24	0.24	0.23	0.23	0.25	0.27	0.26	0.26	0.24	0.26	0.26	0.25
corona ac volts (freon)												
civ	2410	2240	2160	2200	2070	2230	1740	1660	1940	2190	2170	2690
cev	2000	1600	1760	1740	1690	1570	1400	1180	1240	1800	1560	2190
corona dc volts (freon) @ 13.0 kv												
10 sec ct	0.50	0	0	0.2	0.2	0	0.5	0.2	0	0	0	0
dwv @ 14.0 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	2540	•	1830	•	2260	•	1570	•	2320	•	2320	•
cev	2200	•	1400	•	1900	•	1300	•	1600	•	1900	•
corona dc volts (freon) @ 13.0k volts												
10 secs ct	3.00	•	3.20	•	2.90	•	1.50	•	0	•	1.20	•
dwv @ kvdc 20 secs												
pass/fail	pass	•	pass	•	pass	•	pass	•	pass	•	pass	•

Custom -10
Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	1700	1520	1270	1570	1570	1670	1490	1620	1520	1510	1570	1860
cev	1430	1290	1000	1300	1360	1480	1190	1420	1250	1250	1240	1610
corona dc volts (freon)												
@10.0kvdc 30sc	0.17	0.23	0	0.17	0	0.07	0	0.13	0.33	0.23	0.33	0.33
@ 13.5kvdc 5mn	25.00	17.00	9.20	3.00	8.00	8.40	8.20	48.20	19.20	7.00	11.80	27.60
@13.5kvdc 20mn												

Table 6.2-17 Custom 3 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	9.80	9.53	9.6	9.43	9.83	9.76	9.45	10.19	9.28	10.01	10.46	10.67
df	0.0033	0.0036	0.0033	0.0033	0.0031	0.0035	0.0033	0.0031	0.0035	0.0032	0.0028	0.0036
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.39	1.32	1.38	1.39	1.50	1.48	1.38	1.51	1.33	1.48	1.52	1.49
@ 60 secs	0.77	0.76	0.76	0.80	0.84	0.77	0.78	0.84	0.73	0.85	0.86	0.81
@ 120 secs	0.48	0.45	0.44	0.44	0.49	0.46	0.44	0.49	0.42	0.48	0.50	0.46
Freon corona ac												
civ	1230	1040	1020	1000	1000	1040	1030	1100	1090	1000	1080	1140
cev	1110	900	900	850	790	880	910	980	930	880	920	930
dimensions												
length	2.65	2.63	2.59	2.65	2.59							
width	1.55	1.58	1.58	1.56	1.58							
thickness	0.16	0.17	0.16									
width of foil	2.03	2.09	2.06	2.06	2.08							
end margin	.322/.322	.230/.322	.264/.273	.258/.324	2.01/3.00							

Del -10

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	9.80	9.51	9.39	9.42	9.64	9.76	9.39	10.19	9.29	9.82	10.23	9.68
df	0.0031	0.0036	0.0035	0.0039	0.0031	0.0035	0.0033	0.0029	0.0034	0.0033	0.0029	0.0034
ir @ 500 vdc												
leakage current	na											
@ 30 sec	1.61	1.60	2.22	2.52	1.80	1.66	1.63	1.84	1.60	2.16	2.14	1.72
@ 60 sec	0.90	0.90	1.34	1.52	1.00	0.91	0.91	1.04	0.88	1.27	1.25	0.97
@ 120 sec	0.52	0.52	0.87	0.96	0.58	0.54	0.53	0.61	0.51	0.79	0.78	0.55
corona ac volts (freon)												
civ	1050	1000	1010	950	830	1070	1020	820	970	990	930	1100
cev	870	830	810	830	650	910	840	750	810	850	700	890
corona dc volts (freon) @ 13.0 kv											fail	
10 sec ct	5.00	3.90	3.20	0.40	1.20	1.20	0	0.40	0	0.90	@ 12.5	0
dwv @ 14.0 kv												
20 sec ct	pass	pass	failure	pass	pass	pass	pass	pass	pass	failure	•	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	1000	•	•	1000	•	1020	•	1070	•	•	•	1040
cev	820	•	•	780	•	820	•	920	•	•	•	850
corona dc volts (freon) @ 13.0k volts												
10 secs ct	1.00	•	•	0.50	•	0.20	•	1.50	•	•	•	2.00
dwv @ kvdc 20 secs												
pass/fail	pass	•	•	pass	•	pass	•	pass	•	•	•	pass

Del -10

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ												
cev												
corona dc volts (freon)												
@ kvdc 30sec												
@ kvdc 5mn												
@ kvdc 20mn												

Table 6.2-18 Del 2 Capacitor Characterization

Reynolds R-10

AS RECEIVED Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	10.42	9.90	0.03	0.90	9.53	10.39	10.39	9.97	10.15	9.68	9.70	10.37
df	0.0017	0.0019	0.0023	0.0018	0.002	0.0016	0.0017	0.0019	0.0018	0.002	0.0019	0.0017
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.55	1.30	1.44	1.29	1.25	1.51	1.40	1.53	1.60	1.48	1.43	1.35
@ 60 secs	0.89	0.73	0.81	0.73	0.69	0.85	0.79	0.80	0.87	0.82	0.79	0.86
@ 120 secs	0.51	0.40	0.41	0.41	0.39	0.49	0.45	0.44	0.48	0.45	0.44	0.47
Freon corona ac												
civ	950	960	860	790	690	820	840	810	890	820	760	860
cev	630	710	640	660	520	650	660	630	620	630	600	670
dimensions												
length	2.42	2.42	2.43	2.43	2.42							
width	1.50	1.49	1.47	1.49	1.49							
thickness	0.21	0.22	0.22	0.22	0.22							
width of foil	1.91	1.91	1.93	1.90	1.92							
end margin	0.29	0.26	0.26	0.29	0.26							

Reynolds -10

Post burn in test Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	10.33	9.86	9.00	9.87	9.51	10.31	10.35	9.94	10.09	9.65	9.66	10.30
df	0.0018	0.002	0.0021	0.0019	0.0021	0.0017	0.0018	0.0019	0.0017	0.002	0.002	0.0017
ir @ 500 vdc												
leakage current	na											
@ 30 sec	0.70	0.64	1.03	0.63	1.09	1.4	1.31	1.35	1.35	1.26	0.89	1.39
@ 60 sec	0.23	0.22	0.50	0.26	0.60	0.77	0.73	0.73	0.75	0.70	0.42	0.77
@ 120 sec	0.05	0.06	0.25	0.11	0.35	0.44	0.41	0.42	0.43	0.40	0.19	0.44
retest @ 30 sec	1.27	1.05		1.07							1.16	
@ 60 sec	0.66	0.55		0.58							0.65	
@ 120 sec	0.34	0.29		0.33							0.34	
corona ac volts (freon)												
civ	640	880	710	700	730	690	790	680	750	720	740	840
cev	470	570	530	550	530	500	590	500	540	530	540	660
corona dc volts (freon) @ 13.0 kv												
10 sec ct	0.50	2.70	2.50	0.70	0.20	1.50	2.7	0.90	0.7	6.20	1.20	5.2
dwv @ 14.0 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	•	830	•	800	•	740	•	650	•	790	•	750
cev	•	620	•	650	•	540	•	420	•	660	•	540
corona dc volts (freon) @ 13.0k volts												
10 secs ct	•	1.9	•	3.50	•	3.90	•	1.70	•	3.40	•	1.90
dwv @ kvdc 20 secs												
pass/fail	•	pass	•	pass	•	pass	•	pass	•	pass	•	pass

Reynolds -10

Post Life Test 1100 hrs Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	580	970	880	•	860	730	740	730	690	780	750	670
cev	220	720	610	•	660	430	630	540	570	650	600	430
corona dc volts (freon)												
@ 10.0kvdc 30sc	1.00	1.33	5.67	•	10.40	1.43	1.97	2.97	6.07	2.50	1.63	6.30
@ 13.5kvdc 5mn	114.20	38.40	248.40	•	289.20	179.80	135.60	115.20	280.00	206.00	204.00	209.00
@13.5kvdc 20mn												

Table 6.2-19 Reynolds 2 Capacitor Characterization

AS RECEIVED

Serial no.	1	2	3	4	5	6	7	8	9	10	11	12
Capacitance nF	10.76	10.98	10.86	10.87	10.40	10.30	10.71	10.08	10.73	9.85	10.89	10.58
df	0.0035	0.0032	0.0035	0.0032	0.0033	0.0033	0.0033	0.0034	0.0033	0.0035	0.0035	0.0035
IR @ 500vdc												
leakage current	na	na	na	na	na	na	na	na	na	na	na	na
@ 30 secs	1.00	1.11	1.07	1.08	1.01	0.98	1.04	0.99	1.12	0.82	1.06	0.98
@ 60 secs	0.56	0.62	0.60	0.61	0.57	0.55	0.61	0.57	0.65	0.43	0.61	0.57
@ 120 secs	0.32	0.36	0.34	0.35	0.33	0.32	0.34	0.32	0.36	0.37	0.35	0.33
Freon corona ac												
civ	1340	1390	1430	1460	1360	1460	1220	1630	1110	1800	1230	1620
cev	980	1050	1190	990	1150	1130	940	1200	770	1150	1000	1280
dimensions												
length	2.57	2.60	2.60	2.58	2.63							
width	1.34	1.34	1.34	1.34	1.34							
thickness	0.19	0.19	0.19	0.19	0.18							
width of foil	2.05	2.03	2.05	2.04	2.01							
end margin	.242/.268	.266/.302	.266/.266	.256/.294	.238/.369							

Tobe D -10

Post burn in test

Serial Numbers	1	2	3	4	5	6	7	8	9	10	11	12
cap nf	10.72	10.94	10.82	10.83	10.37	10.26	10.67	10.05	10.69	9.81	10.85	10.54
df	0.0029	0.0028	0.003	0.0028	0.0028	0.0028	0.0029	0.0029	0.0028	0.0029	0.0029	0.0029
ir @ 500 vdc												
leakage current	na											
@ 30 sec	1.01	1.04	1.00	1.03	0.97	0.96	1.04	0.97	1.06	0.74	0.86	1.00
@ 60 sec	0.56	0.59	0.55	0.57	0.54	0.56	0.57	0.55	0.60	0.38	0.46	0.56
@ 120 sec	0.32	0.34	0.31	0.33	0.32	0.32	0.33	0.31	0.35	0.21	0.26	0.32
corona ac volts (freon)												
civ	1130	1240	1260	1320	1360	1230	1150	1340	1210	1420	1230	135
cev	870	1000	1040	1050	1040	890	790	860	970	1220	780	1120
corona dc volts (freon) @ 13.0 kv												
10 sec ct	0.20	0.20	0.20	0	0	0.20	0.4	0	2.5	0.70	1.20	0.7
dwv @ 14.0 kv												
20 sec ct	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass	pass

Post Thermal Shock test

serial numbers	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts												
(freon) civ	•	1140	•	1380	•	1230	•	1320	•	1460	•	1400
cev	•	850	•	1090	•	990	•	1060	•	1250	•	990
corona dc volts (freon) @ 13.0k volts												
10 secs ct	•	2.50	•	0.20	•	1.20	•	0.90	•	1.00	•	1.20
dwv @ kvdc 20 secs												
pass/fail	•	pass	•	pass	•	pass	•	pass	•	pass	•	pass

Tobe D -10

Post Life Test 1100 hrs

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
corona ac volts (freon)												
civ	740	610	840	1140	1000	1000	1050	1080	1050	860	1140	1190
cev	550	470	680	890	820	870	820	910	840	690	940	930
corona dc volts (freon)												
@10.0kvdc 30sc	2.70	16.8	0.40	2.40	1.93	1.07	0.87	1.30	3.80	2.63	1.07	0.17
@ 13.5kvdc 5mn	48.80	171.20	45.40	52.60	26.80	46.20	60.80	74.80	59.40	58.20	17.20	30.40
@13.5kvdc 20mn												

Table 6.2-20 Tobe Deutschman 2 Capacitor Characterization

6.2.3 High Voltage Transformers

High voltage transformer evaluation focused on failure analysis, identification of causes of failures and corrective action taken to mitigate these causes.
Two areas of study - wire fatique at stress relief locations and parallel windings expected to share current but not distributing the current evenly - were identified as failure prone mechanisms. The former fails as a result of movement induced fatique at a location already stressed from work hardening and from use of insulation stripping techniques that are damaging; the latter - a long term reliability issue - fails due to overheating from one of the parallel windings carrying most of the current.

6.2.3.1 Wire Fatigue

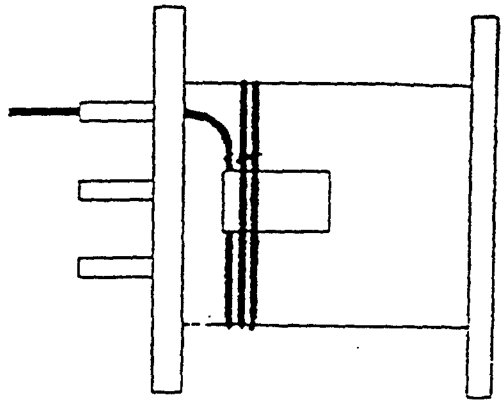
Open windings in the high voltage transformer of the ALQ-135 ECM system were identified as a possible long term reliability issue. After repeated temperature cycling, the windings fracture in an area specifically prepared to provide stress relief against temperature caused movement of the epoxy encapsulant. The stress in this area is induced as a result of insulation stripping to allow soldering, cold working to form the stress relief loop, solder wicking leading to embrittlement and temperature variation during operation which causes fatique due to movement. Figure 6.2.17 depicts the stress relief design. The images are directly from Northrop Grumman workmanship standards. Figure 6.2-18 is a photomicrograph collage of a typical wire break. Note the necking down at the break which is indicative of fatigue failure. It was postulated that the biggest contributor to failure was the surface damage occurring in the stripping process. A model test structure program involving four stripping techniques ie., mechanically scraped, hot wire (thermal), soldering bath and soldering iron - matrixed with a selection of three wire types (200C, 155C and 130C rated wires) - was created to conduct the investigation. A partial test matrix was used since solder pot and soldering iron stripping could only be accomplished on the 155 and 130C wire. Figure 6.2-19 shows the model test structure developed for the test program. The four set test matrix is alternated around the structure four times to average out variations.

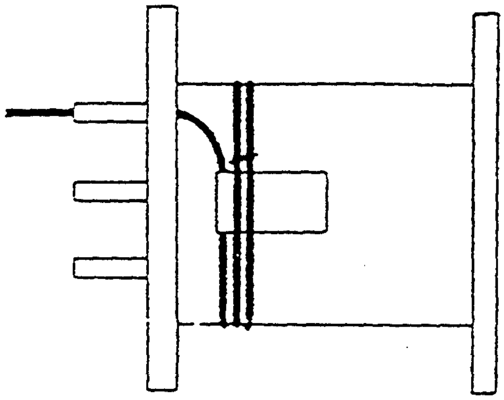
Each test structure was electrically operated to achieve 150C temperature which is the localized uppermost extreme of actual system operation. The test structures were then subjected to standardized eight hour hot-cold temperature cycles(see Volume 2, Section 4.0, Environmental Stress Testing). Failure analysis and MTBF calculations showed significant differences in reliability. Initial comparisons of 200C wire with insulation removed via scraping, thermal (hot wire) and thermal with no solder wicking (solder completely contained within the pin connection) as well as 130C wire stripped via solder pot gave the following MTBFs:

		MTBF
200C	Scraped	363
200C	Thermal Stripped	247
200C	Thermal Stripped, Enclosed	471
130C	Solder Pot	1367

ACCEPTABLE

☞ Stress relieved magnet wire is to have a radial arc from the anchor tape to the terminal pin base.

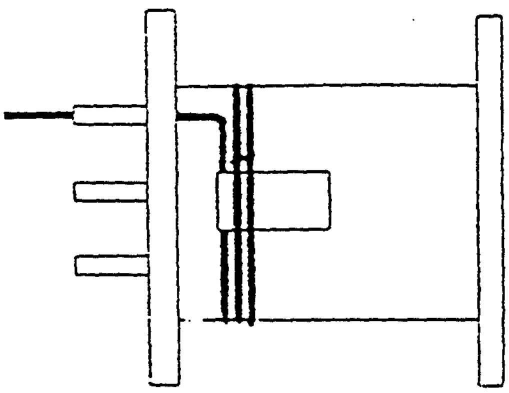




MINIMUM ACCEPTABLE

☞ Stress relieved magnet wire with a slightly less than (true) radial arc.

REJECTABLE



☞ No definitive radial arc.

REJECTABLE

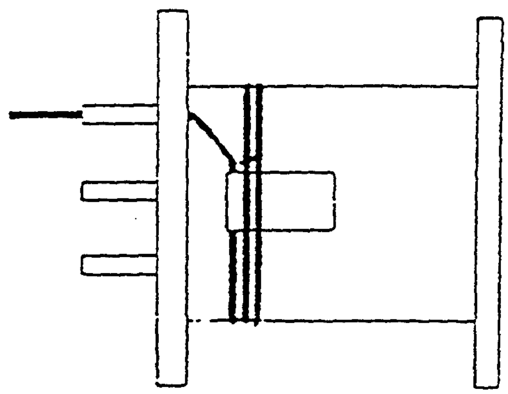


Figure 6.2-17 Stress Relief in Transformer Windings

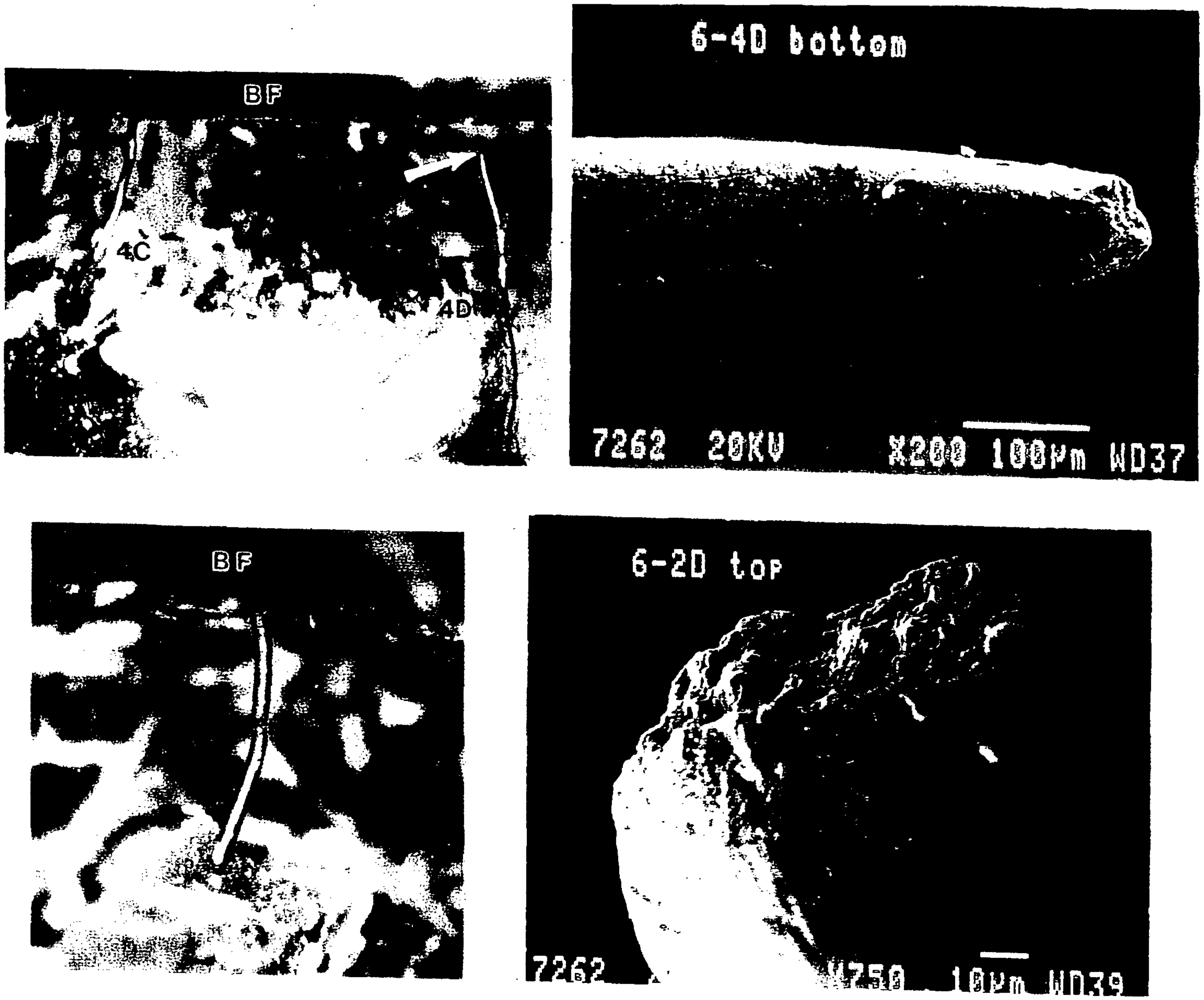


Figure 6.2-18 Typical Wire Break

TEST CONFIGURATIONS

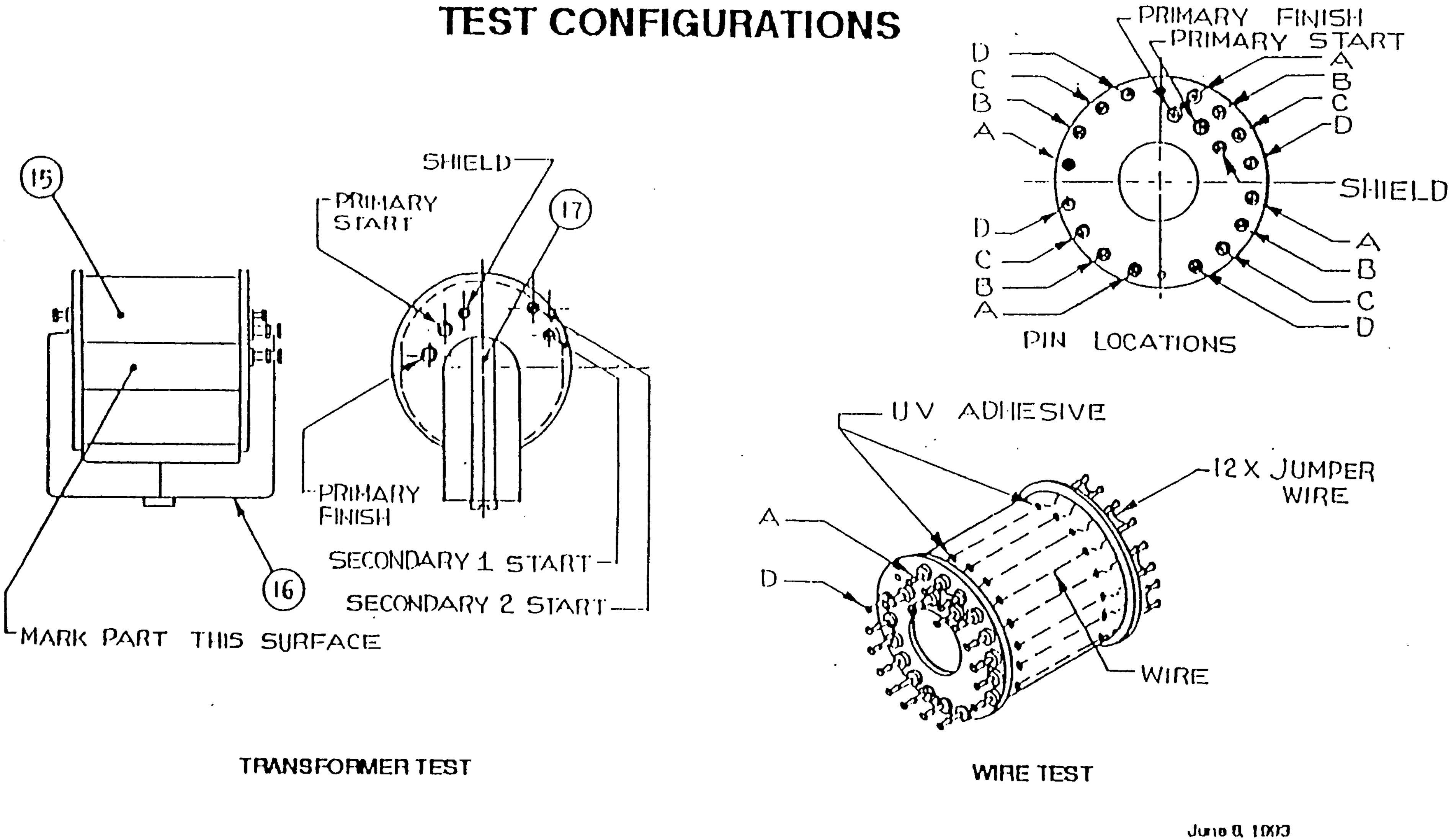


Figure 6.2-19 Transformer Model Test Structure

The next phase took the best and worst case from the above and repeated the test. Consistent results were obtained and led to the abandonment of 200C wire from further evaluation:

		MTBF
200C	Thermal Stripped	592
130C	Solder Pot	1517

A follow on phase added in 155C wire versus 130C and focussed on solder pot versus soldering iron stripping. Results here continue to indicate the superiority of 130C wire and confirm that solder pot stripping is better than using a soldering iron:

		MTBF
155C	Soldering Iron	502
155C	Solder Pot	678
130C	Solder Pot	878

The final phase matrixed 155C and 130C wire with solder pot and soldering iron stripping methods to confirm the previous results:

		MTBF
150C	Soldering Iron	716
150C	Solder Pot	690
130C	Soldering Iron	1278
130C	Solder Pot	1633

The above shows the soldering iron - solder pot distinction to be a wash in 155C wire but in 130C wire, the solder pot gives better results. The total program results clearly show the superiority of using a wire that can be easily and gently stripped - thus minimizing stress damage to the wire. The above results led Northrop Grumman to immediately eliminate the 200C wire that had been a mainstay of this transformer design from inception. This process change and others resulting from the program are described in Section 6.3.

6.2.3.2 Parallel Windings

Parallel windings are frequently chosen over single windings to allow winding flexibility without jeopardizing current handling when tight space requirements have to be met; however, at frequencies typically used in high voltage switch-mode power supplies, parallel windings can result in magnitude and phase differences (unequal sharing) between the windings that increase localized power dissipation and create hot spot locations. In view of these considerations, an effort consisting of the following objectives was undertaken:

o Determine Characteristics of Current Division in Parallel Transformer Windings at High Frequencies

o Demonstrate Methods of Analysis and Test

o Relate Findings to Hardware Examples

An example of the equivalent circuit of a high voltage switching power supply is given in Figure 6.2-12.

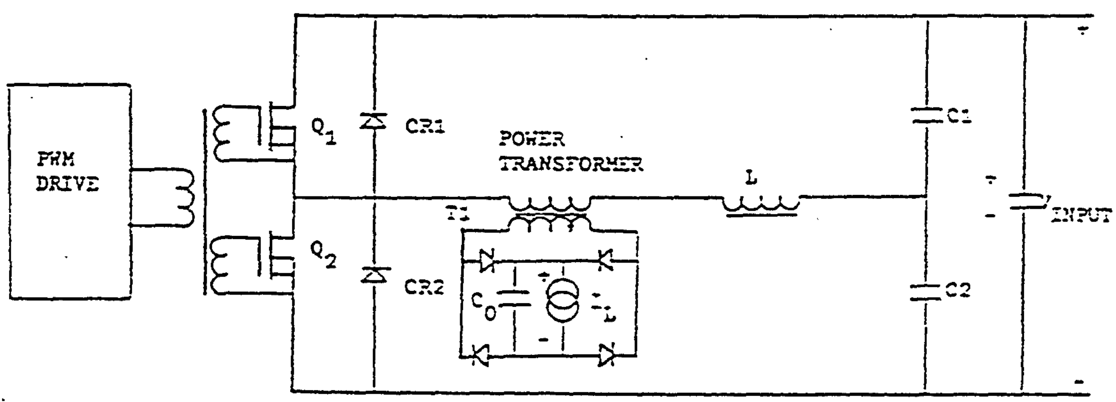


Figure 6.2-12 Circuit Application

Two test transformers (Model Test Structures) and a 17 winding, 1200 watt, 10 kv, high voltage transformer were used in the evaluation. An example of the secondary construction (one layer single solenoid) used in the test transformers as well as the Northrop Grumman ALQ-135 ECM system is shown in Figure 6.2-13. Although not specifically illustrated in this figure, when windings are paralleled they are treated as a single wire for winding purposes and use a single pin connection. Another basic model test structure used in the evaluation is illustrated in Figure 6.2-14. This structure allows any winding to be the primary and the others in combination to be the secondaries. Set #1 in the figure was extensively used.

The test transformers were characterized from 10Khz to 1 Mhz at 50 watts loading. They were also analyzed via circuit modeling. Secondary current magnitude and phase measurements were made for both resistive and rectifier loading to highlight the problems in current sharing.

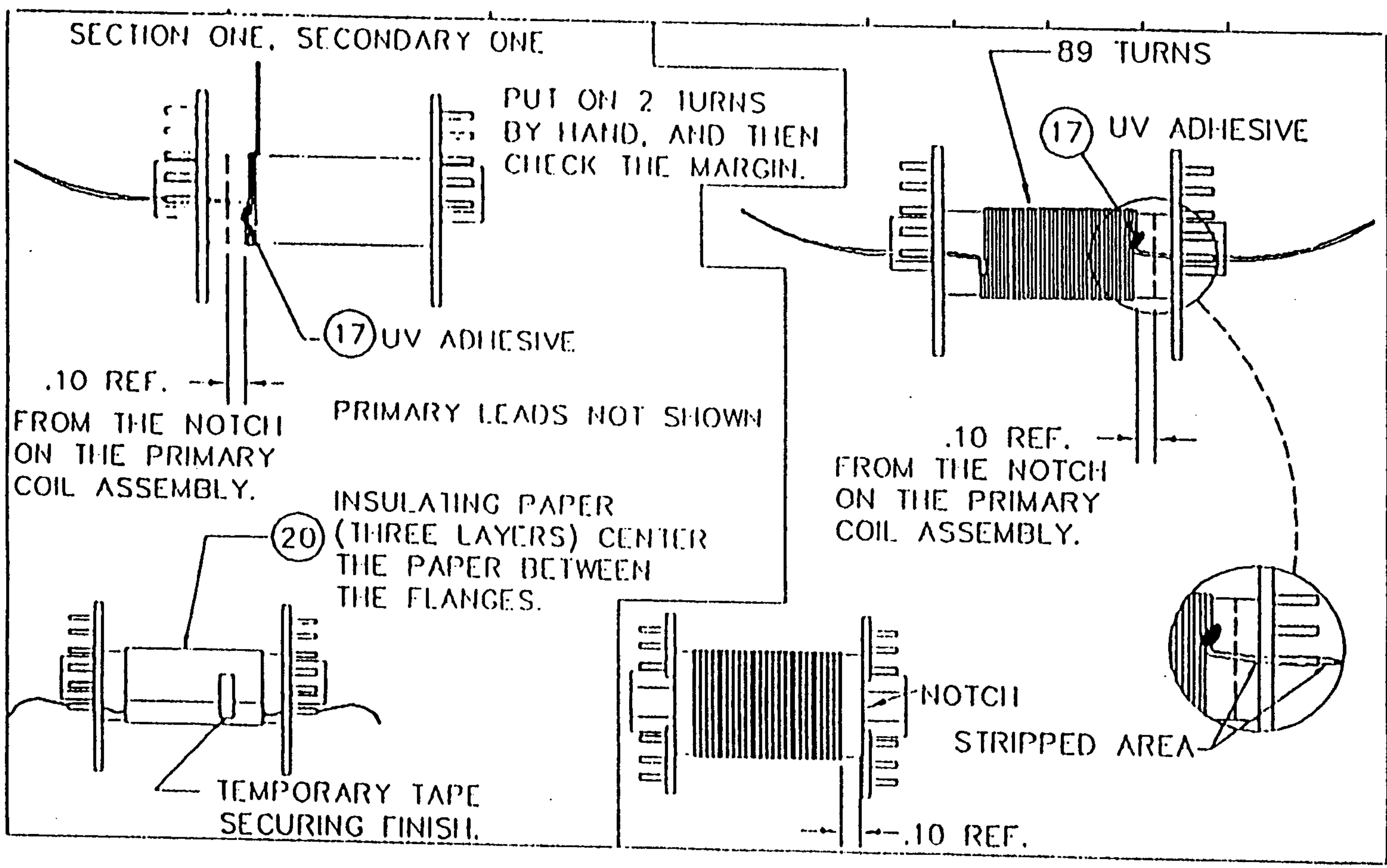
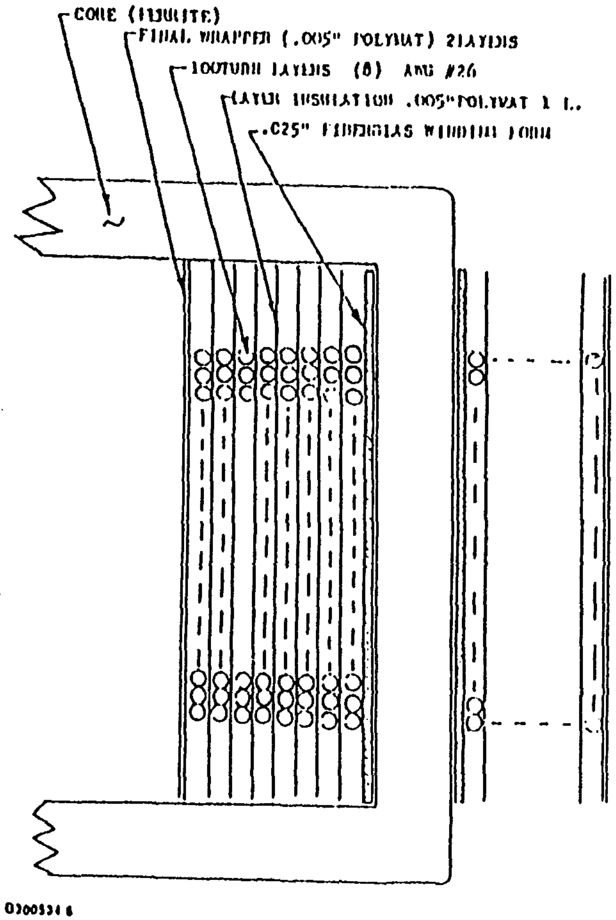


Figure 6.2-13 TRANSFORMER CONSTRUCTION



- o FERRITE 'U' CORE, MN 60 MATERIAL, 1/2" X 1/2" CROSS-SECTION
- o THREE SETS OF TRANSFORMERS
  - SET #1 - EIGHT CONCENTRIC 100-TURN WINDINGS, EACH ON TOP OF OTHERS, AWG #26 WIRE
  - SET #2 - AWG #26 AND #29 ALTERNATING
  - SET #3 - 100 AND 98 TURN WINDINGS ALTERNATING
- o POLYMAT INSULATION BETWEEN WINDINGS

Figure 6.2-14 MODEL TEST STRUCTURES

Figure 6.2-15 shows transformer primary current and Figure 6.2-16 shows the currents (via probe) of a parallel set of secondary windings (curve 1 is the inner winding, curve 2 is the outer winding) for that same transformer. M1 is the algebraic sum of the two curves. It is evident that the currents are substantially out of phase with each other. The measurements are at 40 khz and, though a bit difficult to see, there is a sinusoid at every five division (25 microsecond) intervals. Figure 6.2-17 compares three current probes as a validity check on our findings.The curves are displaced for clarity. Figure 6.2-15 is a repeat of Figure 6.2-16 but at full load and with a probe instead of computed current to look at the sum of the two parallel winding currents. The methods closely track.

Figure 6.2-19 used the model test structure ofFigure 6.2-14 and plots current in each of the two secondaries as a function of frequency. The unit was loaded to 2.5 amps (primary). The thermal dissipation in winding #3 is substantial.

Circuit analysis of the three winding transformer shown in Figure 6.2-20 was conducted to determine the relative effects of equivalent circuit parameters for the ratio of I3 to I2. L1 is the transformer primary inductance. L2 and L3 are the paralleled secondaries. RL is the load resistance and R1, R2, and R3 are equivalent winding resistances. The mutual inductances linking each winding are shown. The ratio of secondary currents can be used to show magnitude and phase differences by mathematically comparing the circuit parameters. Basically, the imbalances are driven by differences in coupling coefficients. As a practical matter, small signal measurements, using an HP 3577A analyzer proved a good method to obtain direct comparative data and thus replaced circuit analysis.

Figure 6.2.21 shows the ratio of outer secondary current to inner secondary current (magnitude and phase) for a solenoidally wound, three wire test transformer. The data is for a resistive load; rectified loading is similar. With reference toFigure 6.2-20 the A/R designation in 6.2-21 is the ratio of current in "outer"winding 5-6 (I2) to the current in "inner" winding 3-4 (I3) swept as a function of frequency. The test vehicle had a 100 turn primary and two 100 turn secondaries. forty kilohertz was chosen as the test point. The plot shows amplitude difference (4.6db) and phase difference (53 degrees).
Subsequently, SPICE analysis authenticated the small signal results and it to was used to identify variations in current distribution. Figure 6.2-22 shows the spice simulation of the circuit. The upper curve is the inner winding and the lower curve is the outer winding. Note the 40 khz amplitudes of 14ma and 6ma respectively in the windings. This compares favorably with the results shown in Figure 6.2-23 (13ma and 8ma) which were real measurements. Finally, Figure 6.2-24 shows the results from an actual operational transformer. The parallel wound secondary contains 117 turns. The A/R ratio showed the currents to be nearly 150 degrees out of phase. The hand drawn circuits on the right depict loading experiments. Loading was significant for corner affects. The lastFigure 6.2-25 is the same transformer with actual wave form measurements at high power. It confirms the previous findings.

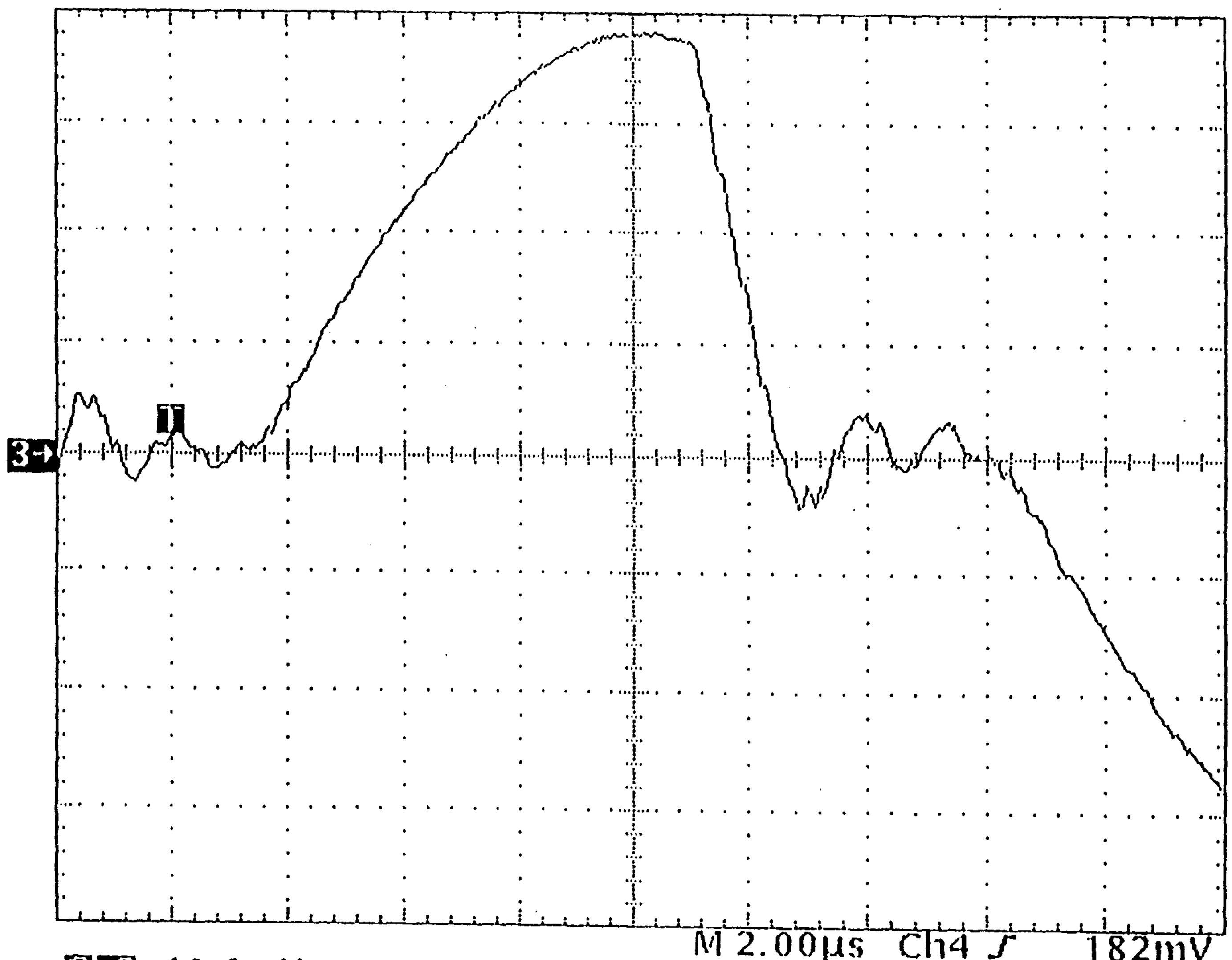


Figure 6.2-15

INVERTER PRIMARY CURRENT

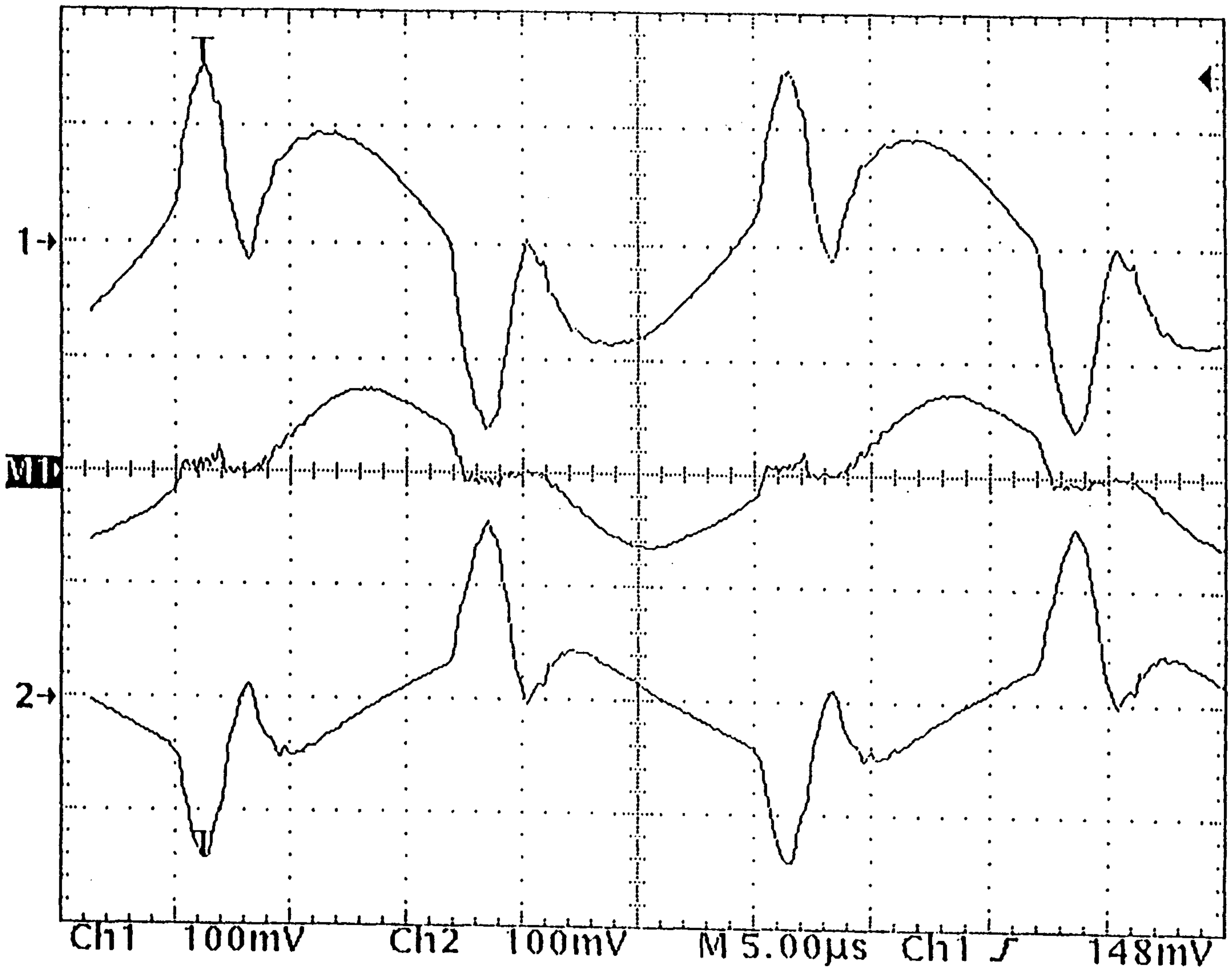


Figure 6.2-16 SECONDARY CURRENTS

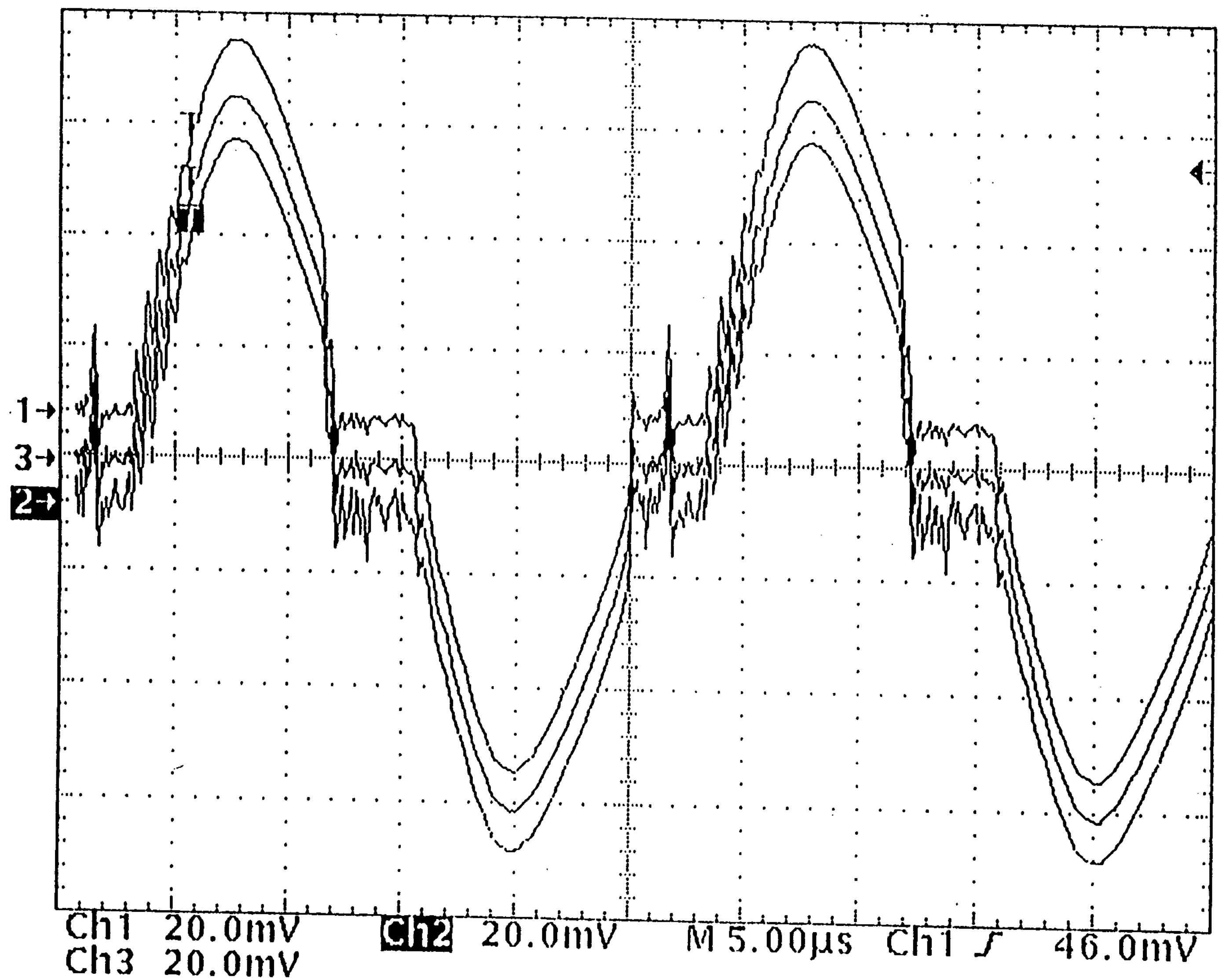


Figure 6.2-17 CURRENT PROBE COMPARISON

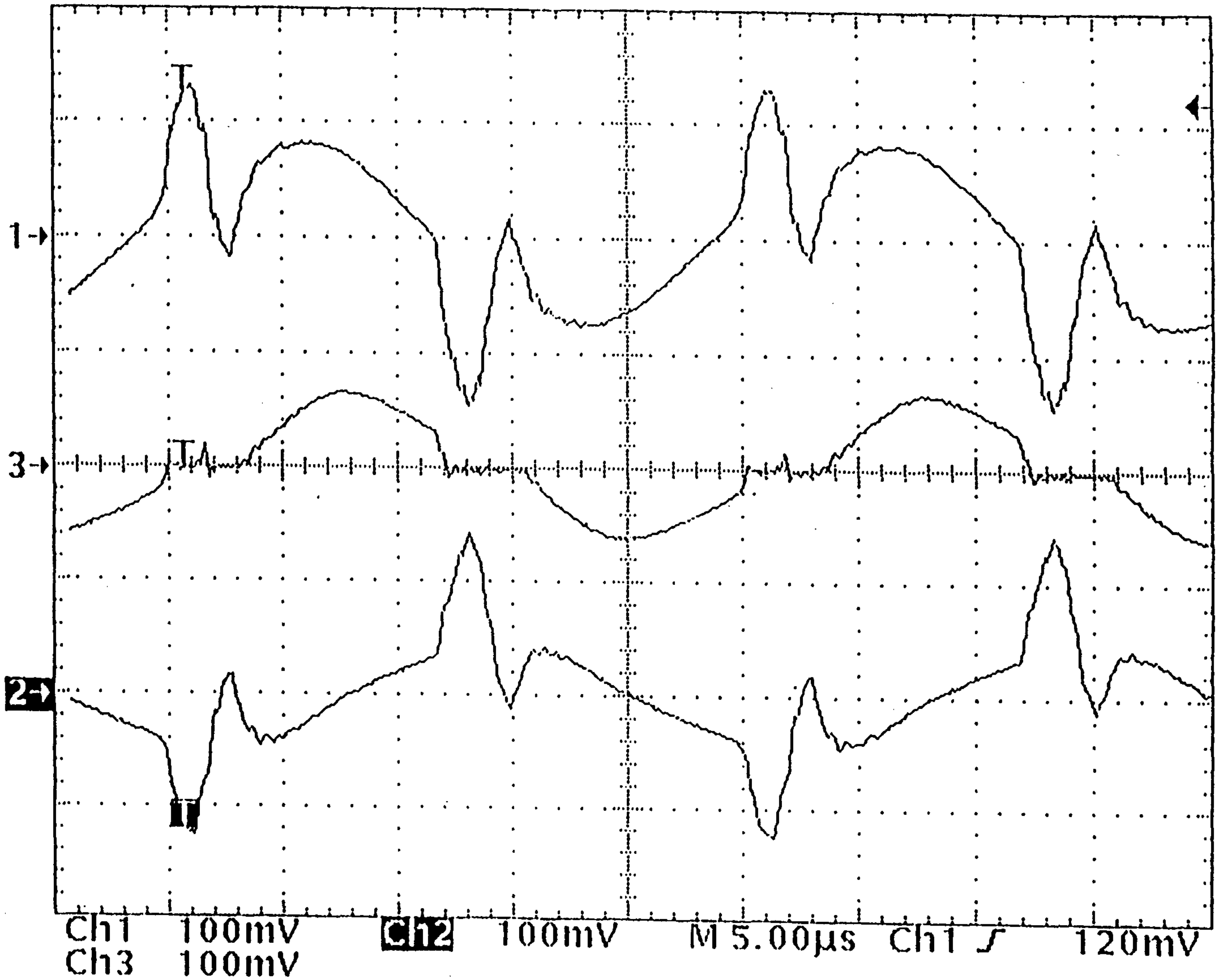


Figure 6.2-18 SECONDARY CURRENTS

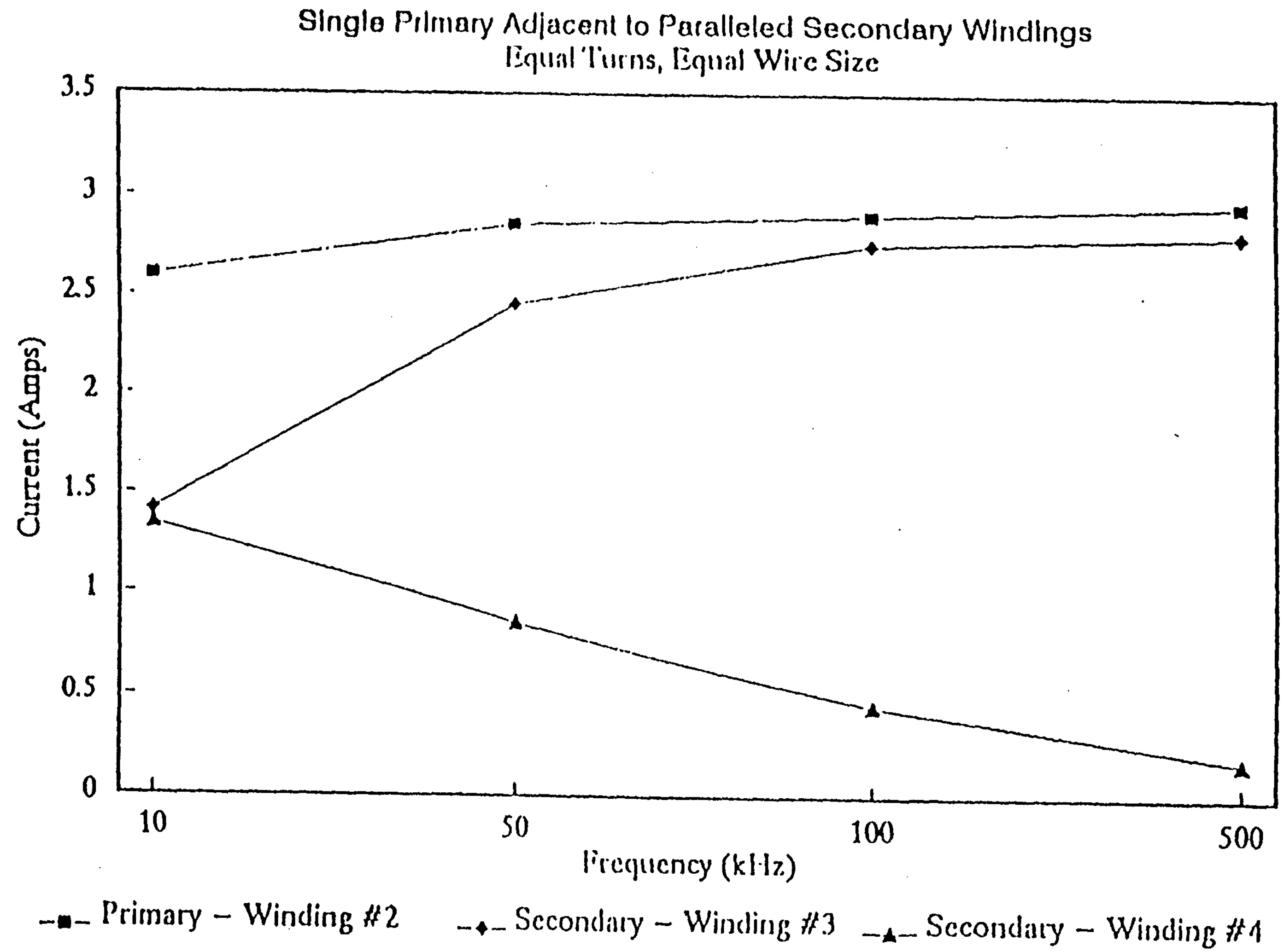


Figure 6.2-19 Winding Current Variation with Frequency

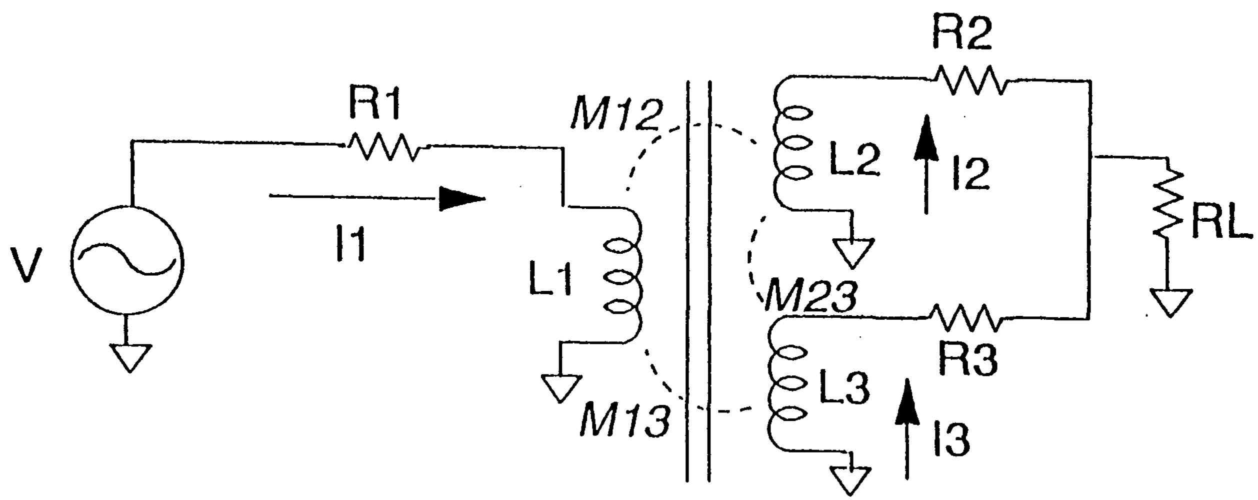


Figure 6.2-20

EQUIVALENT CIRCUIT FOR THREE-WINDING TRANSFORMER

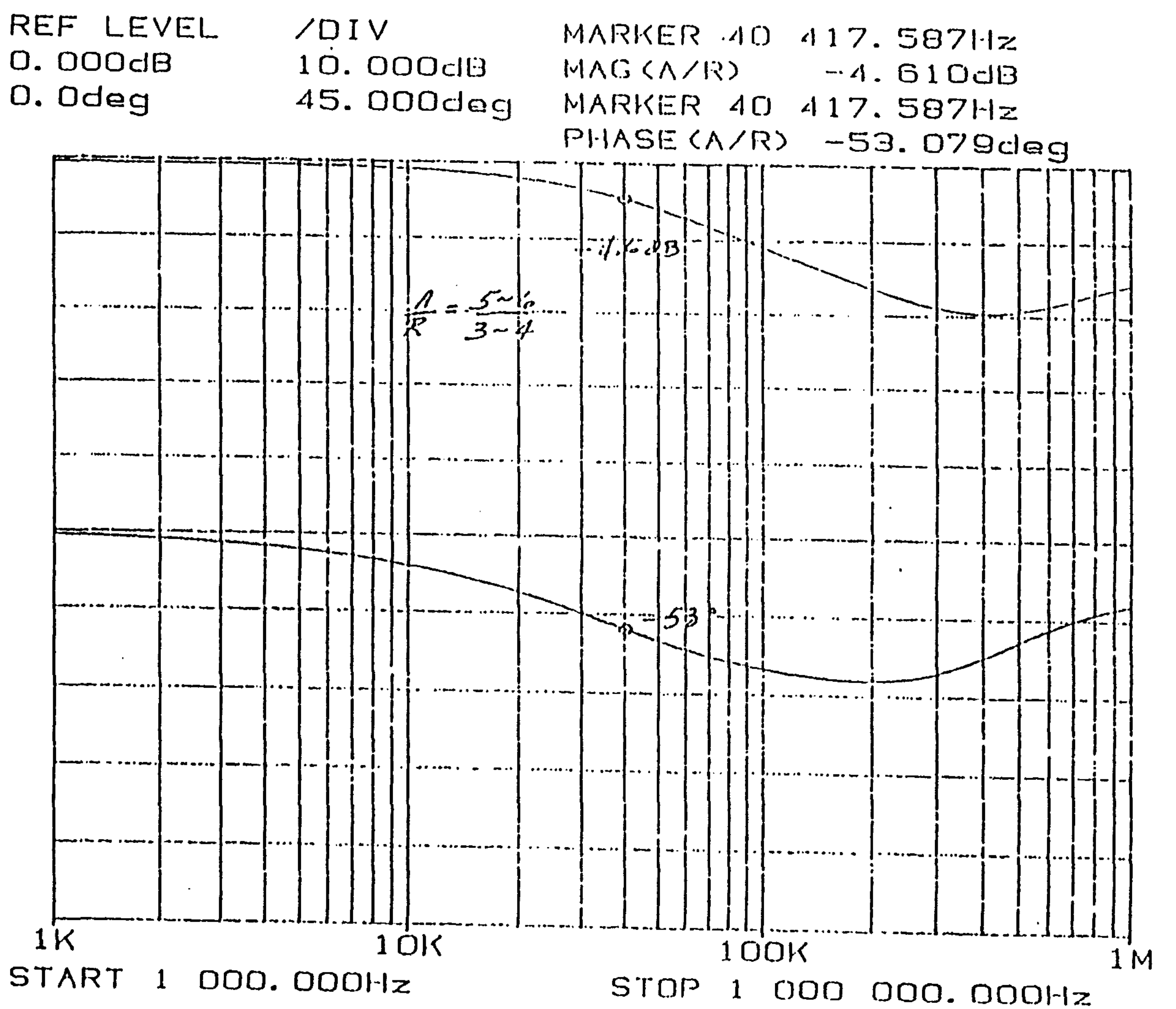


Figure 6.2-21 Ratio of Outer to Inner Secondary Currents

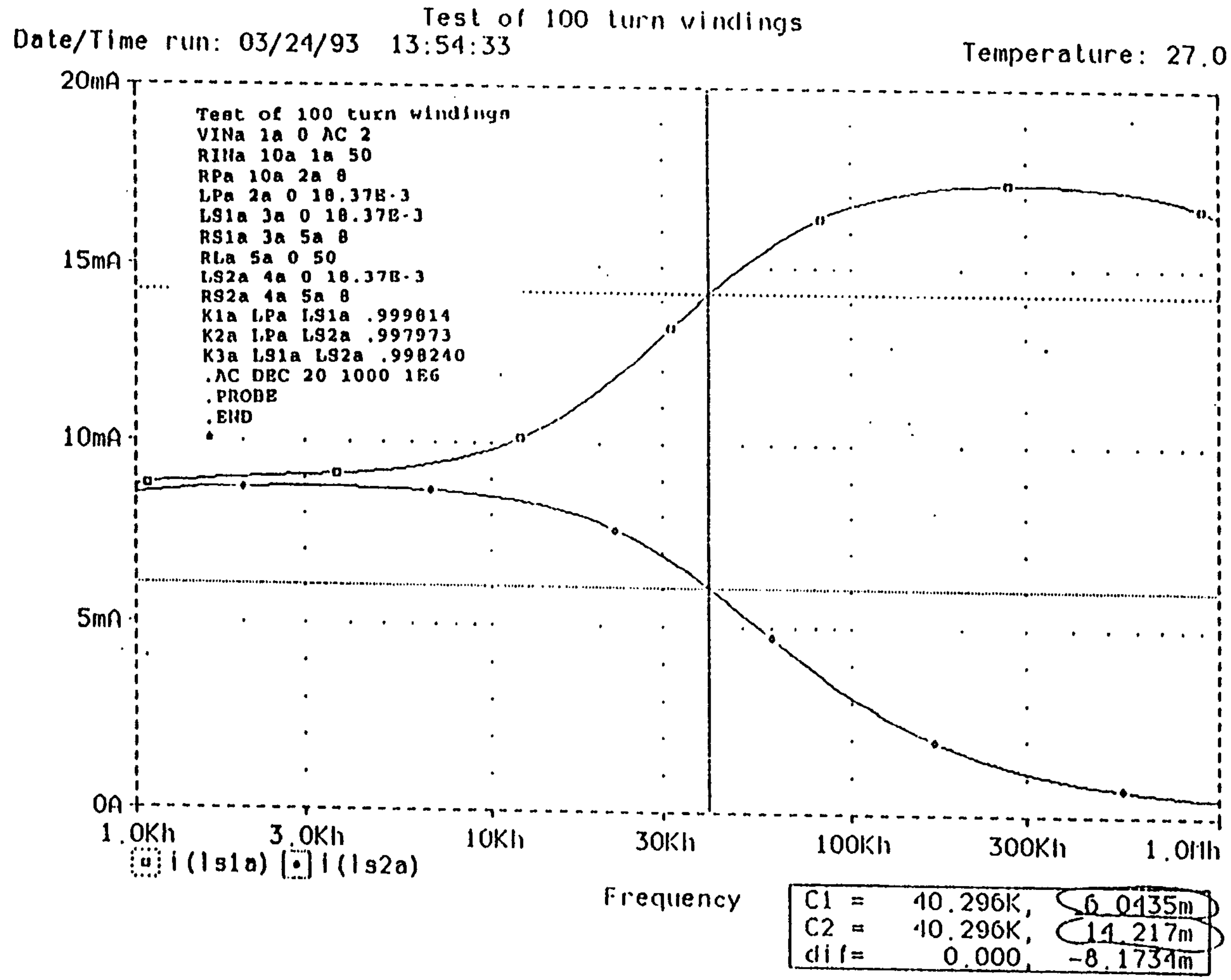
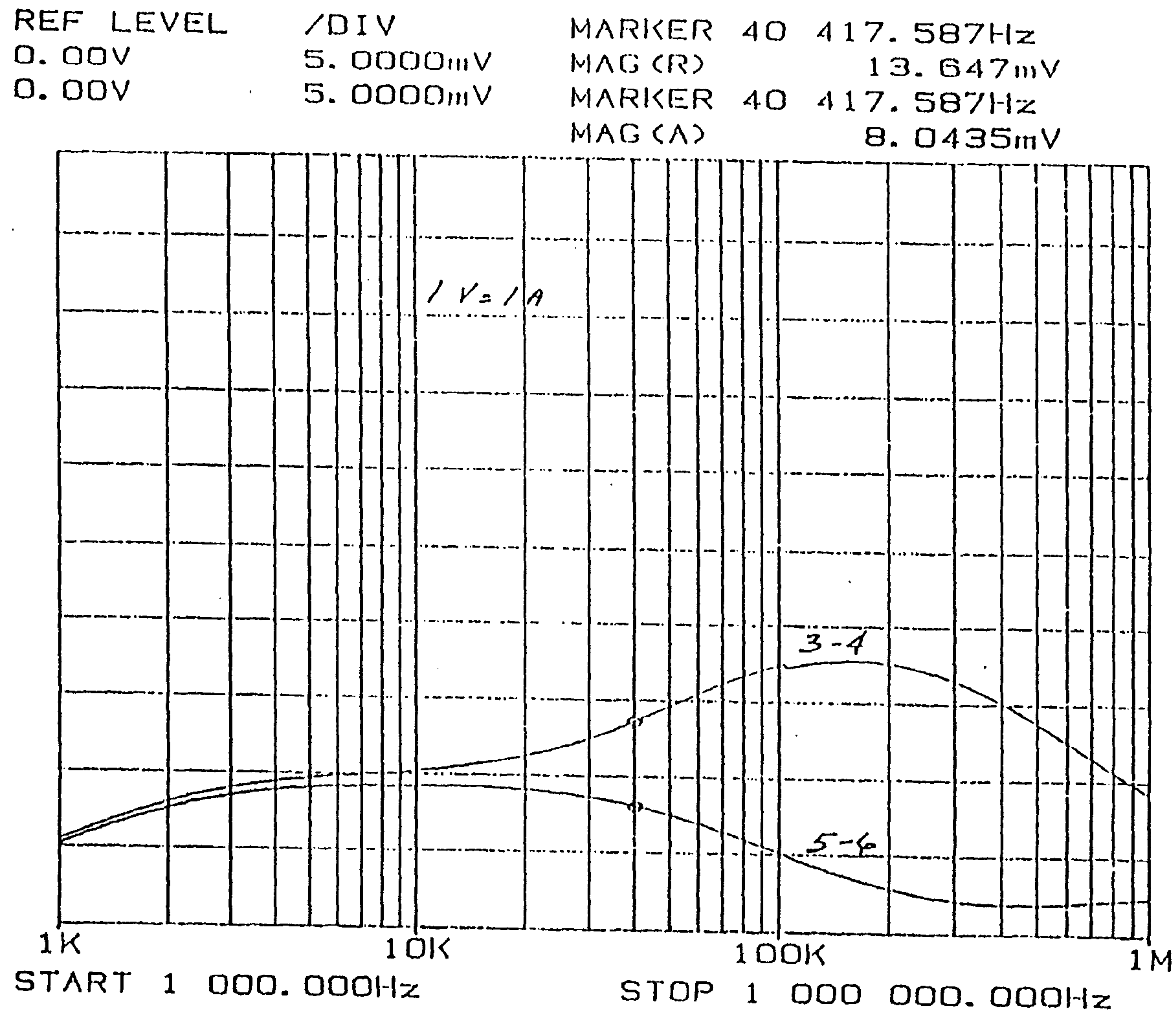


Figure 6.2-22

SPICE ANALYSIS OF THREE-WINDING TRANSFORMER



SECONDARY CURRENT MEASUREMENTS ON THREE-WINDING TRANSFORMER

Figure 6.2-23

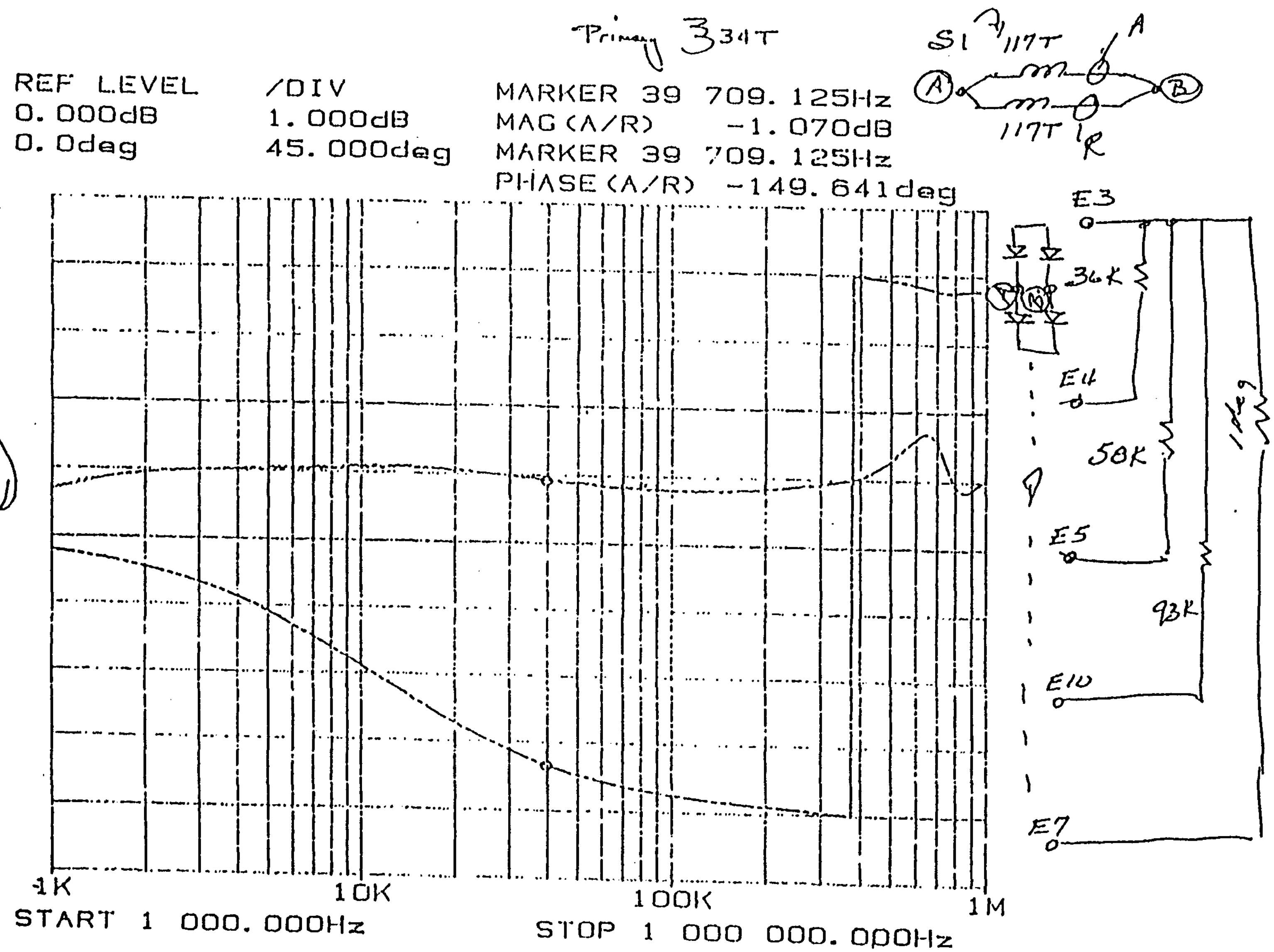


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Figure 6.2-24 Ratios From an Operational Transformer

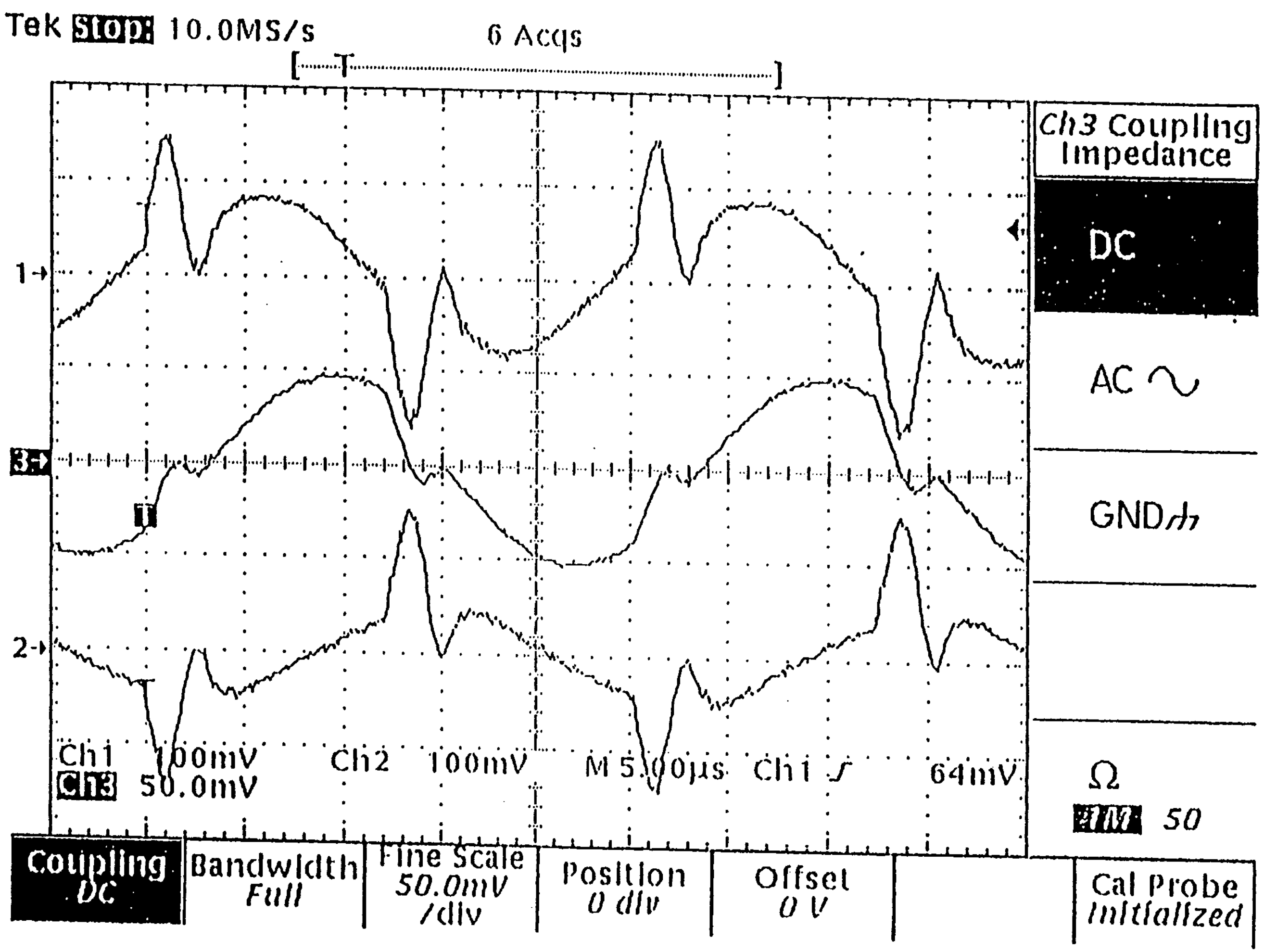

Figure 6.2-25 High Power Wave Form Measurements

A number of observations/conclusions can be made as a result of this study:

- o Magnitude Displacements, Phase Displacements and Circulating Currents Exist and are Real as a Function of Frequency
- o Imbalances are Driven by Differences in Coupling Coefficients
- o Current Sharing Can Be Forced By Interleaving Of Primaries and Secondaries
- o Complex Structures (More Than Three Windings) Are Most Easily Analyzed By Test

It is suggested that further study is required:

1. Use bifilar windings.
2. Parallel the primaries by having an inner and outer winding.
3. Consider resistance control of the windings.

4. Minimize magnetizing inductances in the design.
5. Consider parallel primaries and secondaries on opposite legs of the core.
6. Consider spiral stacks of windings instead of solenoid stacks.

The following is a cross reference guide to specific program details, procedural details and reference information in Volumes 2, 3, and 4 respectively that relate to HV Transformers.

Volume 3 Procedural Details

Section 1.3.1 Test Vehicle Age Testing
A procedure for determining aging characteristics of transformers is provided..

Section 1.3.2 High Voltage Insulation Systems
An approach to measuring AC loss characteristics using a model test structure is discussed.

Volume 4 Reference Information

Section 1.1 High Voltage Transformer Test Structures
This section describes the model test structure used for transformer characterization.

Section 1.6 Impregnated Coils Test Structure
This section described the model test structure used to evaluate the performance of encapsulants used in high voltage transformers.

Section 1.7 Transformers Shielding Test Structure
This section illustrates the model test structures used to measure the effectiveness of various shielding configurations.

Section 2.2 Corona and Shield Effectiveness of Two Types of Transformer Electrostatic Shields Using Model Test Structures.
This section shows the advantages and disadvantages of transformer electrostatic shielding layers made of wound wire versus metal foil. The testing included a model test structure and the AMRAAM high voltage transformer hardware.

Section 2.3 Impregnated Coil Test Results
This section provides the results of the impregnated coils MTS(as described in Section 1.6 of Volume 4). The section includes evaluation of various electrical insulation combinations, determination of the thermal stress behavior on the insulation system, the determination of the AC electrical loss characteristics, and assessment of the processing characteristics of the various impregnants used in the evaluation.

6.2.4 Printed Wiring Board Test Structures

The capability of printed wiring boards to carry high voltage is of concern when space requirements preclude the use of more conventional wiring and harnessing. In small high voltage encapsulated assemblies, PWBs generally serve as interconnects and their performance and reliability should be assessed. This assessment can be reasonably accompolished through the use of Model Test Structures. MTSs serve as a useful tool to:

- DETERMINE VIABILITY OF ETCHED CONDUCTORS (PWBs) AS HV INTERCONNECTS
- ASSESS NEED FOR RADIUSING ETCHED CONDUCTORS
- IDENTIFY ROLE OF ENCAPSULANT TYPE IN HV PERFORMANCE
- DETERMINE EFFECTS OF CONDUCTOR SPACING ON HV PERFORMANCE
- DETERMINE INFLUENCE OF OPPOSED GROUND PLANE (THRU LAMINATE) ON HV PERFORMANCE
- ESTABLISH EFFECTS OF THERMAL STRESSES ON HV PERFORMANCE

The Model Test Structures for Printed Wiring Boards are detailed in Volume 4, Section 1.2. They consist of basic 0.062 inch polyimide boards, using 1.0 ounce copper circuits with 0.5 mil solder plate(fused). The boards were produced at three conductor spacings (0.030, 0.060, and 0.120 inches) and were tested for corona and breakdown in air, in Freon TF and with various epoxy coatings. Results using Epon 825/HV, Scotchcast 280 and Scotchcast 281 as the epoxy coatings are also given in Volume 4, Section 2.4.

6.3 Processes

Section 6.3.1 details the program changes introduced by Northrop Grumman in their HVPS manufacturing processes. As a single, integrated, design and manufacturing facility, the changes are relatively easy to implement - first on a temporary basis to evaluate the changes and then in a second permanent implementation step.
Section 6.3.2 discusses concurrent engineering and QFD methodology used by Hughes in having a subcontractor build the high voltage assembly. This is particularly relevant in development stages and, in fact, whether you have a single site facility or independent facilities, concurrent engineering is a necessity to produce a quality product in a timely manner.

6.3.1 Manufacturing Changes

Stresses in transformer windings are introduced as part of the fabrication process in such areas as winding tension, lead insulation stripping, bending and crimping activities, soldering or spot welding connections etc. These activities pre-stress the locations where the process is performed and subsequently become failure sites after some period of use. In a harsh airborne environment the prestressed locations often become the end of life failure mechanism. In the course of examining high voltage transformer reliability one such stress producing process - high temperature thermal wire stripping of wire insulation (in preparation for making solder connections) - proved especially detrimental to long life performance. Although widely known that mechanical abrasion stresses wire, it was not as readily apparent that stresses from thermal stripping are significant and highly dependent on the temperatures employed. Details of the test results are included in previous Section 6.2.3. The outcome of that evaluation is the introduction of (and recommendation to use) the lowest temperature insulation wire suitable for the operating environment and to therefore use the lowest temperature stripping means (typically a solder bath or soldering iron) to remove the insulation.

To preclude theoretical and empirical analysis of parallel windings (to determine if they equally share current at a given operating frequency), both Northrop Grumman and Hughes have elected to eliminate parallel windings and make do with single solenoid secondaries. For Northrop Grumman this was accomplished with a change in flux density via fewer primary turns that resulted in shifting some of the losses from the copper windings to the core (heat sinking was determined to be adequate for the latter). Simultaneously, the #32 gauge parallel winding set was replaced with #29 wire. Winding difficulties were minimal and the resulting transformer electrical performance was satisfactory. Hot spot locations were eliminated and this design/process change has now been fully implemented into production.

Coefficient Of Thermal Expansion (CTE) mismatches between the various materials and components that typically exist in a HVPS invariably result in the creation of stresses during temperature cycling. A particularly acute problem exists with Silicone rubber due to its relatively high CTE. Even a highly filled Silicone that is typically used by Northrop Grumman to aid in heat transfer and that has side benefit of a lowered CTE is still a problem when comparing its CTE to surrounding environs. The bulk use of silicone for encapsulation has to be assessed for stress affects if

operating requirements are over Mil-Spec temperature ranges. Our findings resulted in localized cracking of the rubber when three fixed sides served to contain the rubber movement. The cracking subsequently becomes a corona location and reduced the assembly reliability. Since the containing walls are at ground potential, it was relatively straight forward to eliminate adherence to one of the walls by introducing a non-stick Teflon coated surface. The subsequent stress relief eliminated the cracking but had a side affect of damaging traces in a flexible pwb due to movement induced work hardening. Essentially, the silicone rubber excursions with temperature were stressing a flexible circuit in the bend radius. This problem was resolved with the addition of some hard wiring to back-up the flexible PWB traces.

The material sections of this report discuss the findings and results from the epoxy and silicone investigations. For the latter, two key parameters of the material, tear strength and compressive modules, have been determined to be useful reliability predictors. As such, these two parameters are measured for each batch of silicone produced and statistically viewed for trend analysis. As part of the program, an independent testing lab, Broutman Associates, has been accredited to measure these same parameters - thus maintaining strong oversight of performance. The Dock-to-Stock arrangement with Grace Specialty Products for the silicone, allows direct shipment to stock and/or to the production floor with only a paper check of the accompanying data sheet. Should statistical analysis show a trend toward the sigma limits, samples of the product can be immediately diverted to Broutman if required. The Dock-to-Stock arrangement has been fully implemented in the form of a purchase specification.

Reynolds Industries findings of Teflon shrinkback as the most significant failure cause of high voltage connector assemblies has led to the development of a specification limiting the amount of acceptable shrinkback. Samples from various wire suppliers prove that controlled processing during the extrusion operation can produce wire with low inherent stress and therefore minimum shrinkback during temperature cycling. Testing also showed that there was minimum relationship between corona results and connector reliability.

As a general follow-up to the use of statistical analysis for silicone batch evaluation, it was determined that several test sites in the overall HVPS manufacturing process should also have statistical process control. These test sites proved invaluable in assessing the quality state and trend of the product:

HV Transformer - Primary Inductance
- Primary Resistance
- Voltage Ratio

Cathode Voltage - Light Load, Initial
- Full Load, Initial
- Light Load, During Burn-in
- Full Load, During Burn-in

Finally, temperature cycling of key subassemblies and top level assemblies proved immensely valuable in not only comparing performance when changes are made, but serving also as a useful screen to sample production for subtle changes. Details of the environmental test are in Volume 2, Section 6 of the Manufacturing Guidelines. When the cycling is coupled with spot altitude/corona checks, a very important evaluation tool is created. The corona test procedure is included in Volume 3, Section 1.1.

6.3.2 Concurrent Engineering Methods

The relatively high failure rates experienced for high voltage power supplies during the development process, and in service, are evidence of the fact that they are very difficult products to engineer and manufacture. Deceptively simple circuit diagrams belie the extreme difficulty of simultaneously satisfying the often conflicting requirements set that includes small size, light weight, low cost, high voltage, high power output, high reliability, low voltage stress, high efficiency, low heat dissipation, low electro-magnetic emanations, and many others. Critical variables in the power supply, such as component and materials properties, heat, voltage stress, component and conductor locations, shielding, etc., can interact together in complex ways that can be difficult to anticipate during the development process. HVPS productization is a formidable discipline that taxes the skills of the finest engineers and scientists.

Additional details on design considerations can be found in Section 1.0 of Volume 2. Information includes a discussion of the Quality Function Deployment and Design of Experiment tools used in this program. Additionaly, high level general design and packaging considerations are discussed.

As shown in Figure 6.3-1, the HVPS should be viewed as a system that incorporates six different types of "subsystem" elements. These are design, packaging, components, materials, manufacturing processes, and testing. These elements do not represent independent variables in the power supply. Rather, they tend to interact strongly, and this is a characteristic of HVPSs that sets them apart from other types of devices that, while they may contain more components and functions, they are far easier to engineer and build. For example, specific electrical designs obviously affect the components used. Voltage and power dissipation levels inherent in the design affect not only the types of components chosen, but also the type of materials to be used, as well as the form that the HVPS's packaging will take. The types of component and packaging materials used will also affect the choice of encapsulation material and the manufacturing processes used. The specific tests and test methods chosen for an HVPS is a function of the specific choices made for all of the other five variables. These variables will interact with each other whether or not those interactions have been planned. They will strongly affect the HVPSs performance.

It is often the case that the expertise in each of these areas resides in different individuals. While these individuals all contribute to the final product, they do not necessarily do so in the most efficient manner. The traditional method of HVPS engineering is shown in Figure 6.3-2. The process is a sequence of steps carried out be specialist/experts in those fields. The initial activity, the electrical circuit design, is performed by one individual or team, thepackaging design is then performed by specialists in that discipline, with the aim of implementing the electrical design in hardware that fits the desired outline.

Components are then selected to fit the packaging design by specialist/experts in those disciplines. At this stage, there is often some degree of interaction between the packaging

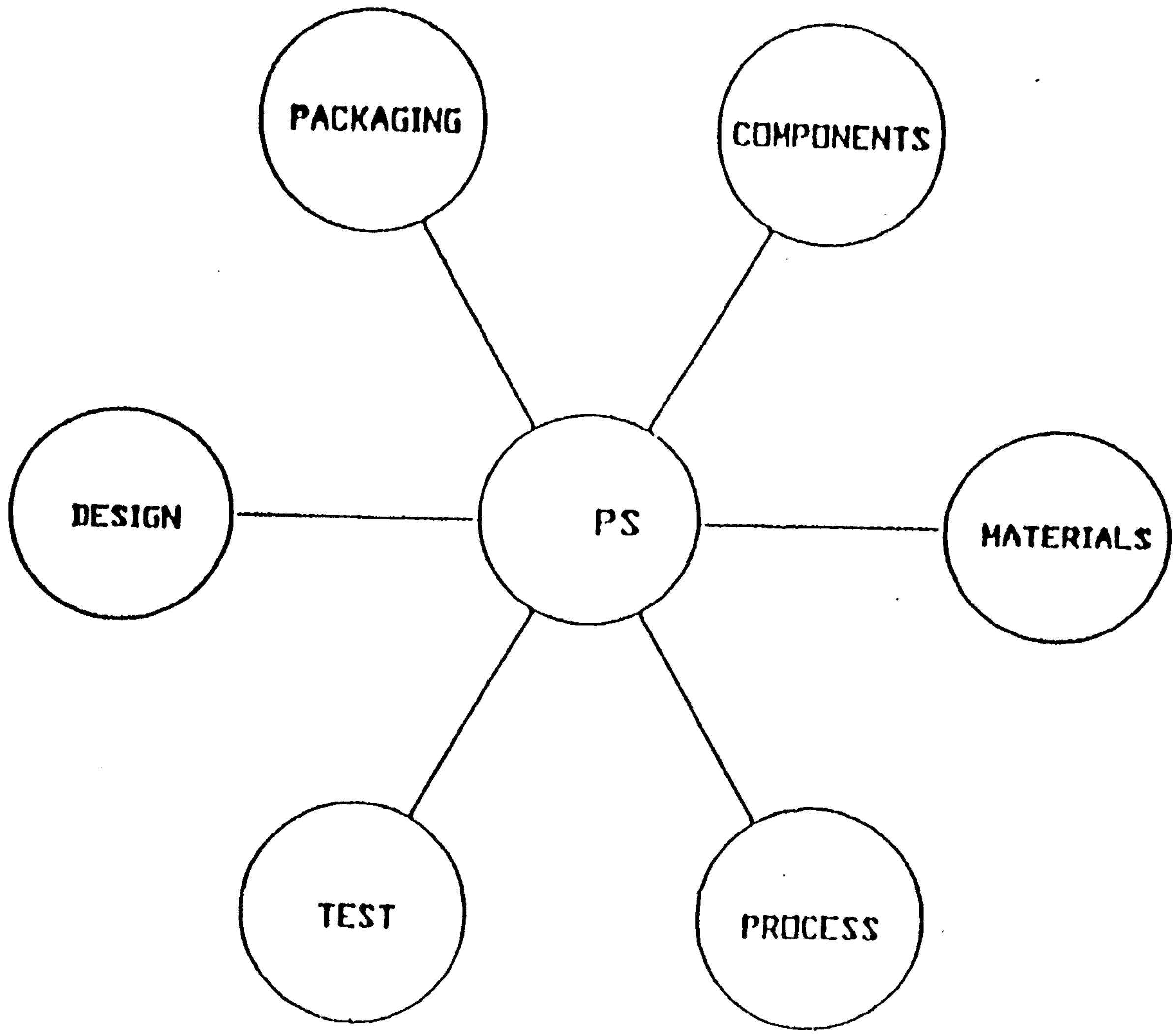

Figure 6.3-1 Elements of a Power Supply

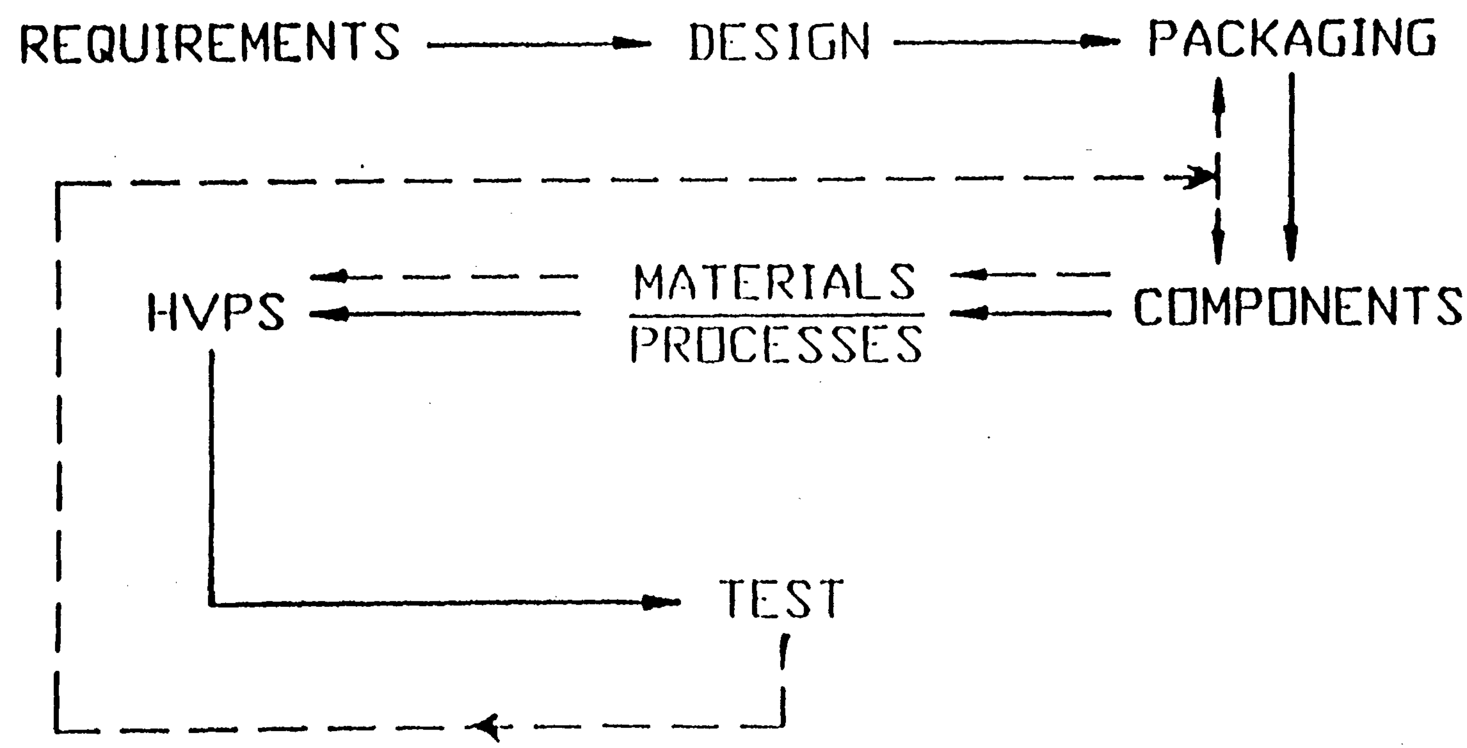

Figure 6.3-2 Serial Approach to Designing High Voltage Power Supplies

designer and the component engineer that results in the selection of components that will fit the design's physical envelope. Materials are then selected by a materials expert. At this stage, generally the best that can be hoped for is a compromise that may accommodate many of the conflicting demands imposed by all of the previous selections.

Specific test methods are often identified after the fact, and are generally selected from a portfolio of standard tests that the manufacturing house has used over the years for assessing the conformance of a wide range of power supply types to general design requirements. These standard tests are often applied without much consideration for unique aspects of the specific product's potential problems, and its specific, detailed requirements.

While this description may somewhat overstate the fragmentation of the HVPS development effort with some manufacturers, few will question that there is generally insufficient interaction among the specialists that are responsible for the different key aspects of the HVPS. As a consequence, critical interactions between variables may be overlooked, and when a prototype HVPS is built and tested it is quite common for it to fail. The development effort then shifts into a failure analysis mode, and the results of those studies fuel changes in one or more of the factors discussed above. The HVPS development effort then progresses around the circuit shown in Figure 6.3-2 again - and often, again and again. It is not uncommon to proceed around this loop five or even ten times in the case of an HVPS with requirements that are particularly difficult to meet. This in an inherently inefficient and expensive process. It also can result in extensive schedule delays for the HVPS production effort, and for the system program as a whole.

Our view is that the "parallel processes' methodology shown in Figure 6.3-3 is the better method to use when designing or redesigning an HVPS. In this method, a multi-functional team of experts in the disciplines of design, packaging, components, materials, manufacturing processes, and testing, works together during all phases of the power supply development effort. In so doing, the expertise of each expert complements that of the others, and interactions and problems can be anticipated before the design is implemented in hardware. Designed experiments, using model test structures, can be performed during the design effort to answer questions or points of disagreement that arise as the team proceeds through the design effort. In addition, performance-related questions can be raised, and risk areas can be identified early in the process, in a thorough and efficient manner.

The use of concurrent engineering teams is not a novel idea - it has been practiced or attempted with greater or, generally, with lesser success for many years. The difficulty that teams encounter when attempting to practice concurrent engineering is the lack of a methodology that structures their cooperation. Yet the complexity and difficulty of the HVPS development process makes it an ideal candidate for concurrent engineering. At the beginning of this program, we considered that the greatest contribution to HVPS manufacturability would be the creation of a methodology by which multi-functional teams could work together effectively and efficiently. We believed that, because of the great difficulties that concurrent engineering teams had met with in the past, that a new approach, and a new set of concurrent engineering tools, would need to be developed and proven in order for concurrent engineering to become an established process with HVPS manufacturers.

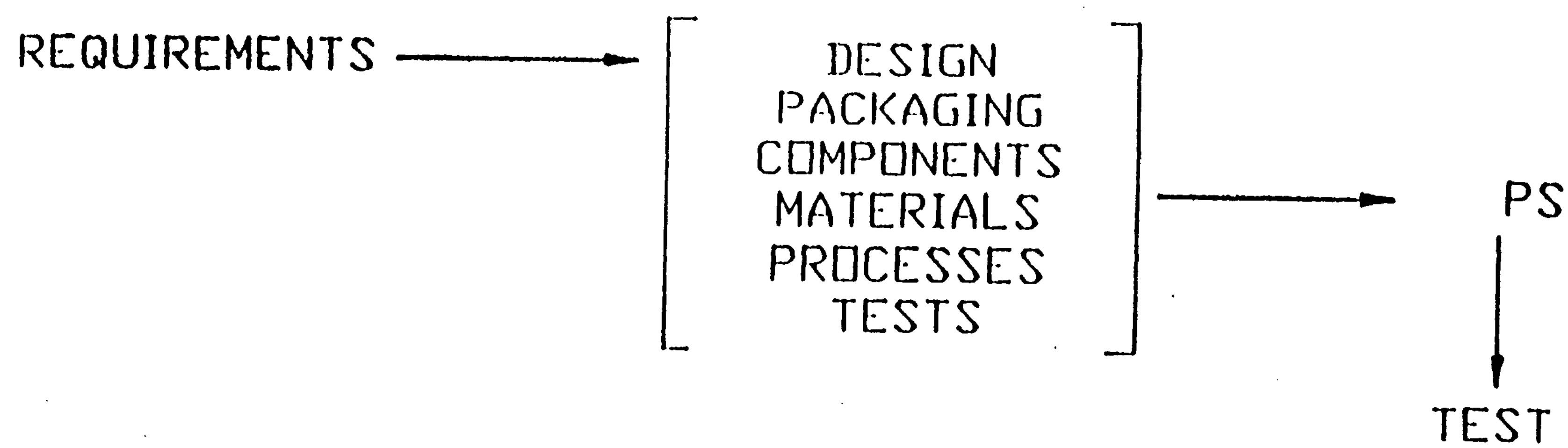

Figure 6.3-3 Parallel Approach to Designing High Voltage Power Supplies

Thus, the heart of the effort in this program became the development and demonstration of these new concurrent engineering methods and tools for the HVPS development process. The foremost among these tools, and the main concurrent engineering vehicle at all conceptual levels of the HVPS, is the implementation of Quality Function Deployment (QFD) for HVPSs. This methodology is described in Appendix 1-1 of Volume 2 of the Design and Manufacturing Guidelines. The QFD process frequently raises questions that must be answered, and highlights risk areas that must be addressed, during the development process. The Model Test Structures (MTS) - Design of Experiments (DOE) methods are used for these purposes, and are described in Section 3.2 of Volume 2 of the Design and Manufacturing Guidelines.

A third concurrent engineering tool developed during the ManTech program, and documented throughout the Design and Manufacturing Guidelines, is the data that we obtained on critical power supply components and materials, such as diodes, capacitors, encapsulation materials, etc. The results of these characterization studies forms a self-consistent data set that can be used during the QFD process to select component and material candidates, or against which other candidates can be judged if they are tested according to the methods used to collect the tabulated results. Through the use of these methods the concurrent engineering team can quickly and efficiently perform its most important function - the implementation of the power supply's requirements, from the highest conceptual level of the power supply as a system, to the lowest level of the individual components, materials, and processes, in its final hardware.

We developed the QFD effort as a part of the first, engineering methods development phase of the Manufacturing Technology for High Voltage Power Supplies program. It is also very important to confirm the results of our concurrent engineering design process through the construction and evaluation of hardware. In order to demonstrate the efficacy of our methods, we decided to redesign a Hughes HVPS which had undergone considerable development, and for which there was considerable manufacturing experience. For these reasons, we chose the HVPS HV module that is a part of the AMRAAM missile's radar system. This HVPS has been in development and manufacturing for well over ten years, and it has gone through several redesign and improvement cycles during this process. We proceeded to assemble a multi-functional team that included personnel from both Hughes Aircraft and OECO Corporation of Milwaukie Oregon, our AMRAAM HVPS power supply manufacturing subcontractor, and tackled the AMRAAM radar's A-3 high voltage module.

We began the implementation of the method on the A-3 module with a kickoff meeting at Hughes Aircraft's El Segundo CA facility. Meeting attendees included personnel from two Hughes locations (California and Arizona), and personnel from OECO. Technical personnel in the meeting represented all of the above six disciplines, and program management personnel from both companies were also present. The team reviewed the top level packaging decision: whether to use a solid, liquid, gas, or solid/gas hybrid encapsulation system. The QFD form used was the top level form shown Figure 27 of Appendix 1-1 of Volume 2 of the Design and Manufacturing Guidelines.

The team discussed the advantages and disadvantages of each approach and concurred on the

ratings associated with each of the major HVPS criteria when applied to each packaging approach. The team then reviewed the rankings and discussed the selected approach, solid encapsulation, versus the other approaches, to have a "sanity check" on the method. The team agreed on the technical requirements for the power supply and agreed on general requirements for certain of the electronic components that would be used in the redesign. Finally, the team members agreed upon assignments for certain critical activities to be performed by subteams or individuals prior to the team's next full meeting.

Team members agreed to perform the initial circuit redesign, to develop specific concepts for packaging elements and transformer designs, and to gather data to identify potential candidate encapsulant materials, diodes, capacitors, resistors. In each case, the agreed upon HVPS requirements were to be used as a guide.
A second meeting was held at OECO's facility in Milwaukie, Oregon. At that time, designs and data were analyzed, and QFDs were performed. Subsequent to that meeting, the electrical design was formalized, and components and materials were selected on the basis of QFDs.

The team's first assembly activity was to build a manufacturing prototype, a so-called "engineering development module (EDM)." During this phase of the design process, details of the packaging design and layout were finalized through the use of short QFDs designed to answer simple choices. The specific form of the charts used for these simple analyses were developed by OECO from our QFD charts. An example of these simple QFD charts is shown in Figure 6.3-4. It shows a simple QFD used to make and document the decision to use a mounting plate that was attached to the "ManTech" A-3 module before potting - a potted mounting plate. The other two possibilities, which were rejected as a consequence of the QFD, were the use of a mounting plate that would be attached to the module after the module was potted, and the possibility that we might dispense with a mounting plate for the ManTech module. In this analysis, improved thermal energy transfer was considered the most important factor, with a weighting of 9. Weight reduction was considered the least important factor, with a weighting of 1. In the analysis, the +, 0, -, and * ratings were each multiplied by the weighting factors. The potted mounting plate showed a balance of four more +'s than -'s, with no *'s or ?'s. The other approaches fared less well. Comments on the form enhance the value of the QFD document as an historical record.

Simple forms of this type are appropriate to use when the decisions to be made and documented depend on only a relatively small number of properties. Under such circumstances, the simplicity of forms like these is a real virtue. Simple analyses like that of Figure 6.3-4 can easily be prepared by a single individual. It is crucial, however, that the QFD analyses, and their implications, be a subject for discussion by the full concurrent engineering team. On more than one occasion, other considerations, introduced by team members who were not experts in the particular discipline involved in the issue under consideration, altered the team's perspective.

Because of the expense and time involved in assembling the team, which included personnel located in California, Arizona, Oregon, and Colorado, in one room, subsequent meetings of the full team took place through team conference calls, which occurred at least once a week.

MNTPLATE.XLS

QFD ANALYSIS

POWER SUPPLY LAYOUT

PROGRAM: A3 MAN-TECH
Item: Mounting Plate
Prepared By: J. Stanok
Date: 11-05-93

file: johns\20598\qfd\mntplate

Requirements		Design Candidates: Potted Mounting Plate	Attached Mounting Plates	No Mounting Plate			Comments
Improve Thermal Energy Transfer	9	+	-	-			
Eliminate Assy Nuts	3	+	+	+			
Meet Specified Mounting Hole Config	5	-	-	-			Spec change approval required
Reduce Material Costs	3	-	0	+			Elimination of mounting plate may require additional machining operation to maintain flat mounting surface
Reduce Labor Costs	3	0	+	+			
Reduce Weight	1	0	0	+			
							Consider alternate mounting plate design.
	?						
	O	4	4				
	-	8	14	14			
	+	12	6	10			
	•						

Figure 6.3-4 Simplified Quality Function Deployment (QFD) Chart

For these calls, subteams at each location assembled in a conference room, and the subteams were connected to each other by telephone. When possible, written materials were FAXed to all parties prior to the start of each of these meetings. In the case of the telephone conference calls, as well as the face-to-face team meetings, consensus decision making was used, with the program manager or his designee acting as a facilitator for the process, and only rarely making unilateral decisions. Technical decisions were always consensus decisions.

When the EDM was tested, a problem was discovered that was related to the transformer construction. Fortunately, in the design of the EDM's transformer, the leads of all of the transformer windings, even those that were to be internally connected, had been brought outside of the transformer so that each individual winding could be accessed. Experiments suggested the need for a redesign of the transformer's primary winding. This was done, and the new transformer design was tested prior to the assembly and potting of the three deliverable HVPS HV modules that represented the hardware product of this demonstration phase of the ManTech program. These deliverable modules performed as anticipated in all respects.

The EDM module, and the three deliverable HV modules built by Hughes and OECO on this program are shown in Figures 6.3-5 to 6.3-12. As will be seen from Figure 6.3-12, the proof-of-design unit number 3 (POD-3) was instrumented with thermocouples placed in critical locations within the body of module. These were for use during life-testing and stress testing, to help evaluate the actual temperature distribution throughout the module, and compare it to the distribution calculated during the design effort.

These HVPS modules passed all functional tests, showed a desirable two-fold reduction in phase noise, contained one-third less parts than did the original AMRAAM design, and cost about two-thirds as much as did the original AMRAAM HVPS design prior to the inception of the ManTech redesign effort. While these units are now awaiting the lifetests and qualification tests that will confirm their reliability, we anticipate enhanced reliability as a result of the smaller number of components, the smaller number of interconnections, and the internal design of the module, which provides precise locations for all of the components and interconnections, a feature not shared with the original design. Heat transfer between the diode stacks and the mounting plate / heat sink has also been enhanced.

This redesign activity, from the beginning of the design phase to the delivery of the final hardware, was completed in about seven months time, a new record for a HVPS development effort at Hughes Aircraft. It was also completed with only one design flaw, which was corrected through analysis of a single EDM unit. The deliverable units were built immediately after this EDM unit.

We consider the ManTech redesign of the AMRAAM HVPS HV module to be exceptionally successful, due to the fact that the ManTech PODs met or exceeded all of their technical and quality requirements, as well as the very ambitious requirements for cost savings and reduction in development schedule time. The use of our concurrent engineering methods was an indispensable element in the successful build.

The following eight photographs are of Hughes/ OECO high voltage potted assemblies incorporating the techniques and technology of the HVPS Manufacturing Technology program:

Figure	6.3-5	Top View, EDM Module
Figure	6.3-6	Perspective View, Proof of Design (POD) Unit #1
Figure	6.3-7	Top View, POD Unit #1
Figure	6.3-8	Connector Edge View, POD Unit #1
Figure	6.3-9	Perspective View, POD Unit #2
Figure	6.3-10	Top View, POD Unit #2
Figure	6.3-11	Connector Edge View, POD Unit #2
Figure	6.3-12	POD Unit #3 with Thermocouple Instumentation

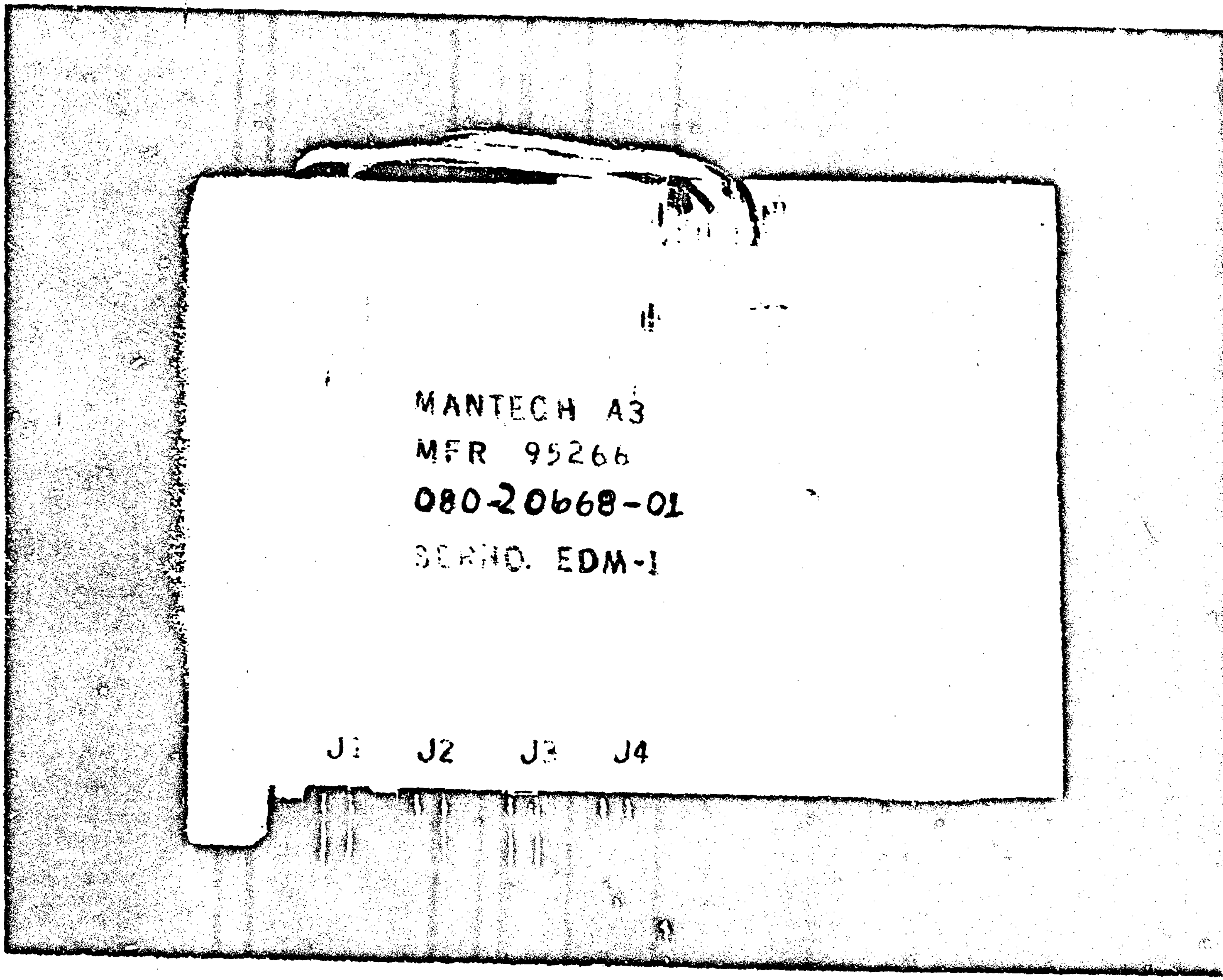

Figure 6.3-5

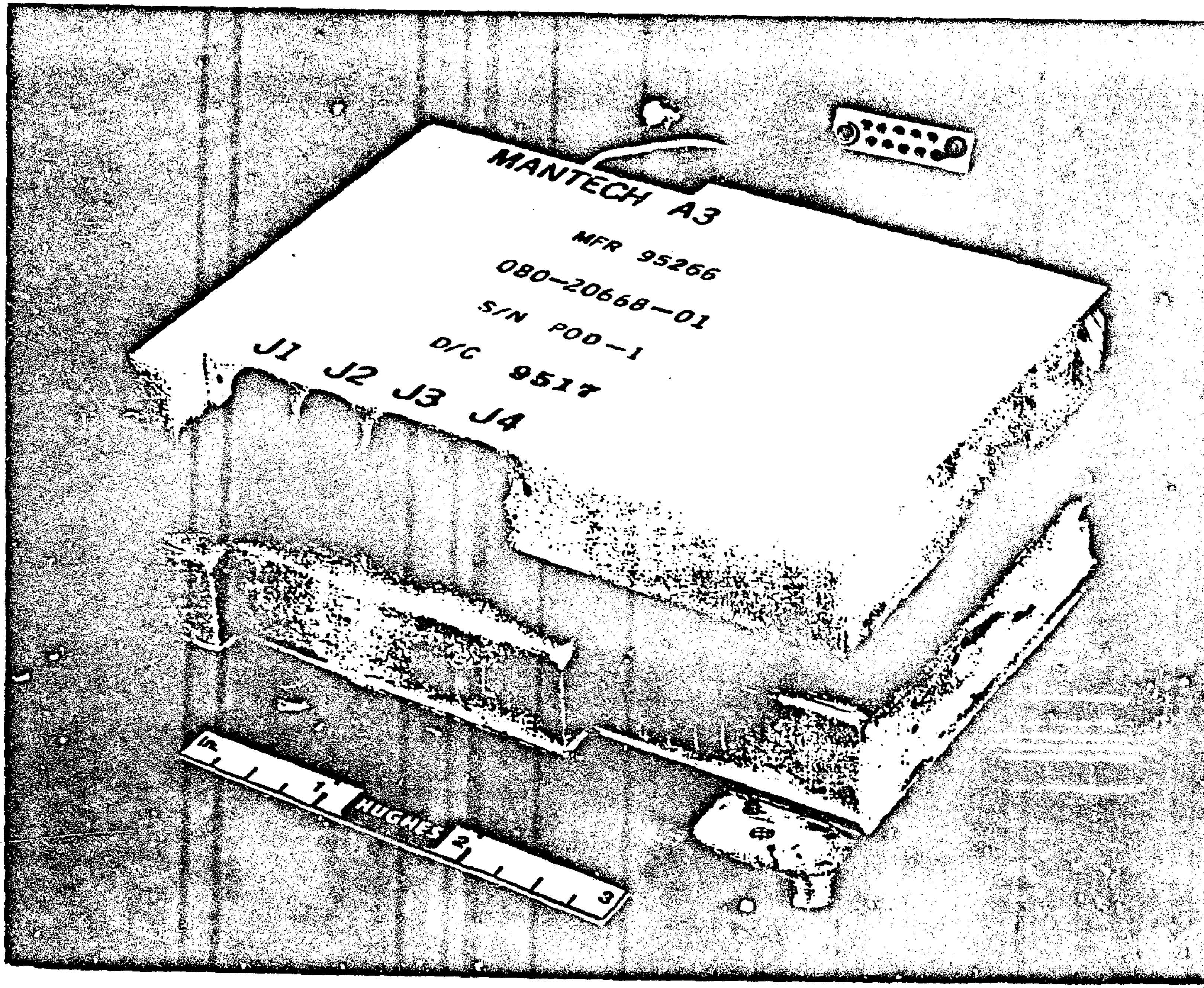
MANTECH A3
MFR 95266
080-20668-01
S/N POD-1
D/C 9517
J1 J2 J3 J4
HUGHES
1
2
3

Figure 6.3-6

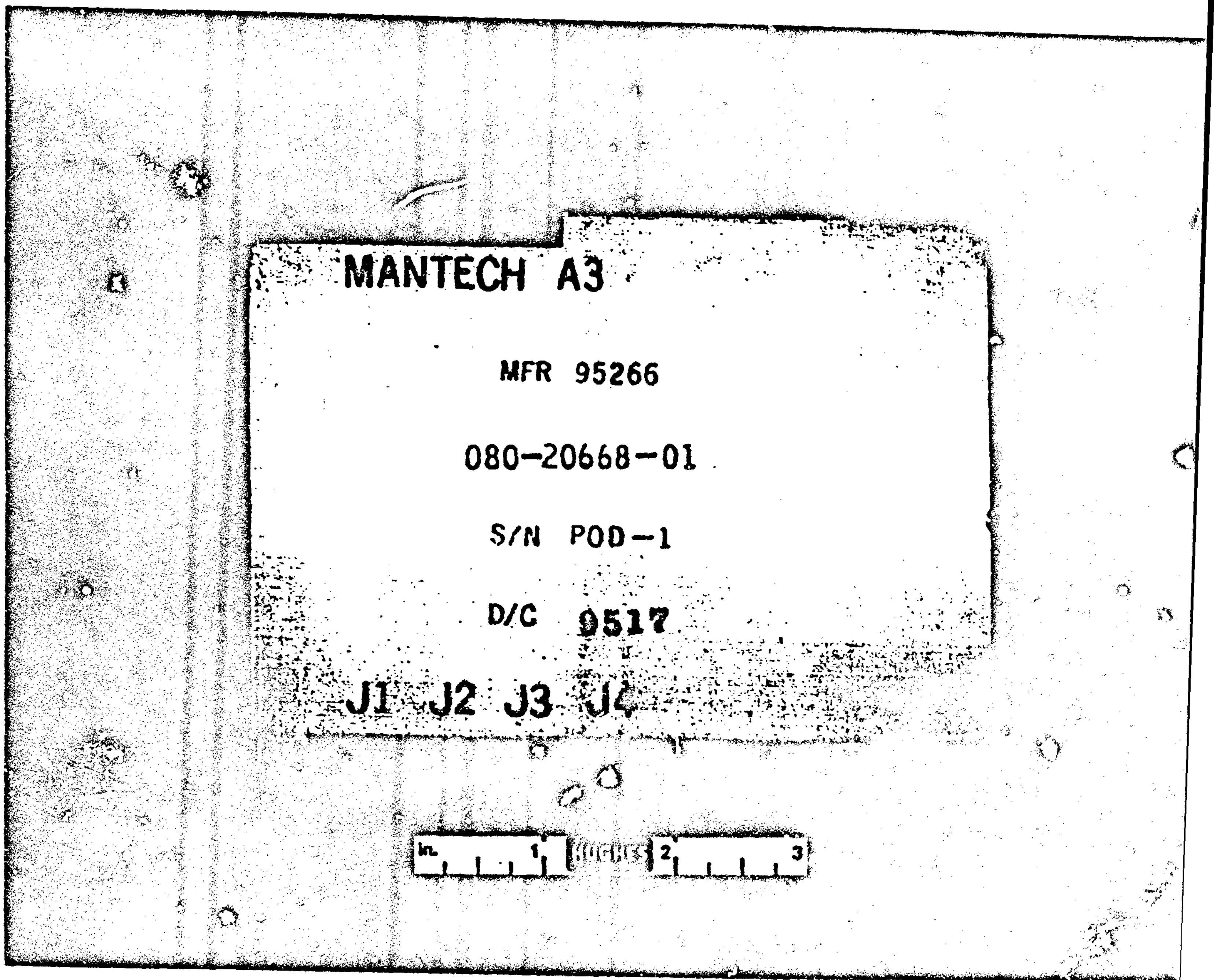
MANTECH A3
MFR 95266
080-20668-01
S/N POD-1
D/C 9517
J1 J2 J3 J4
in. 1 2 3

Figure 6.3-7

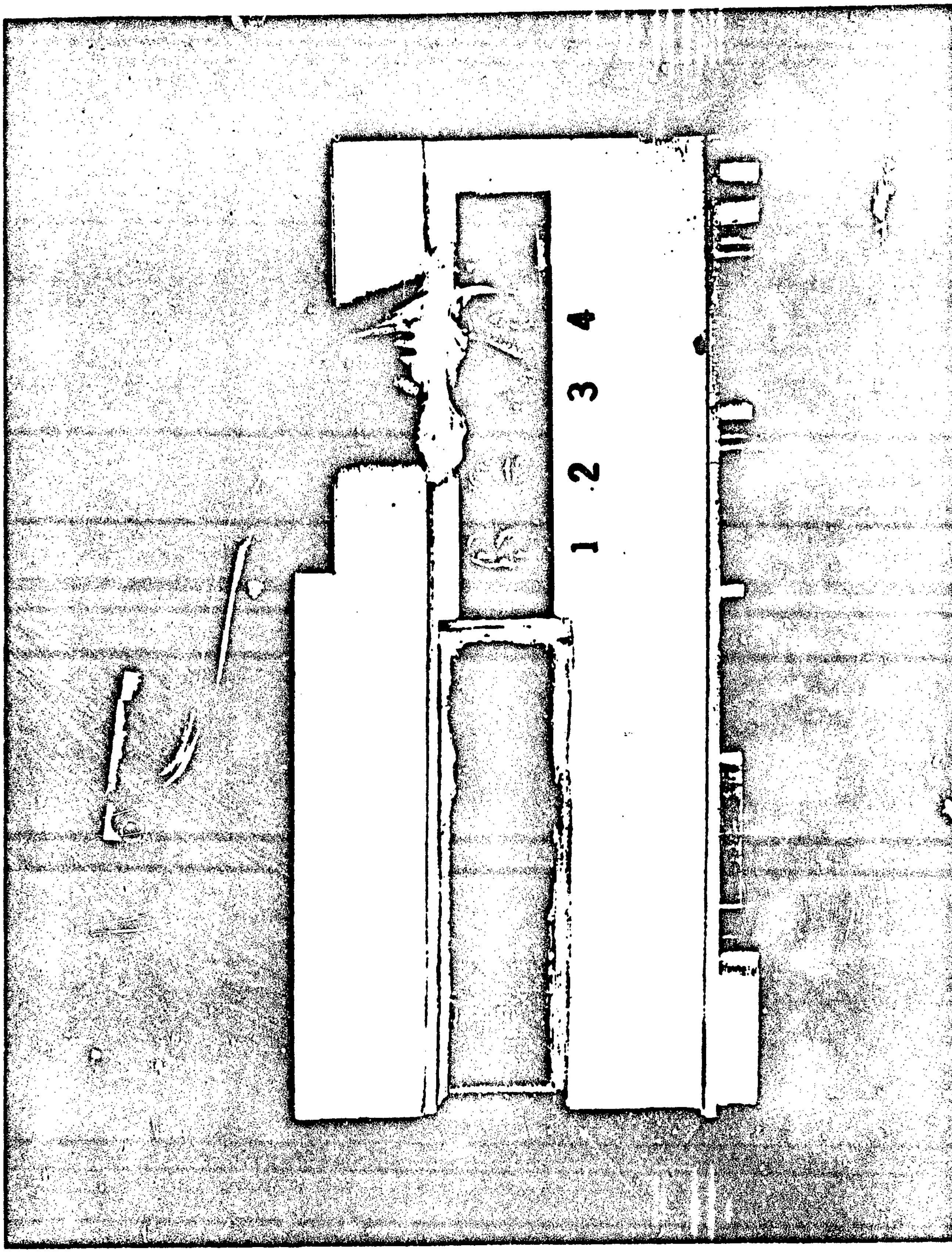

Figure 6.3-8

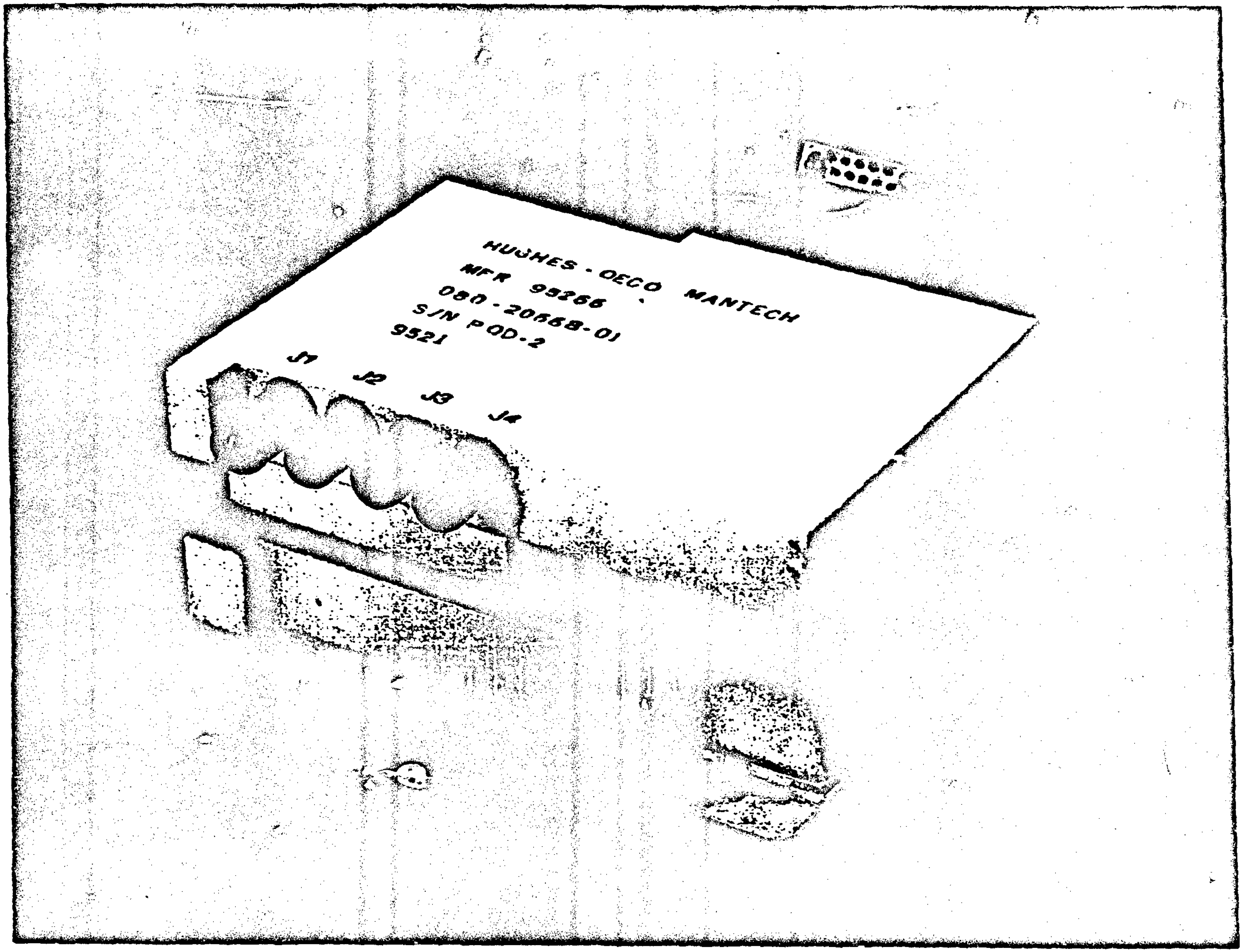
HUGHES - OECO MANTECH
MFR 95266
080-20668-01
S/N POD-2
9521
J1
J2
J3
J4

Figure 6.3-9

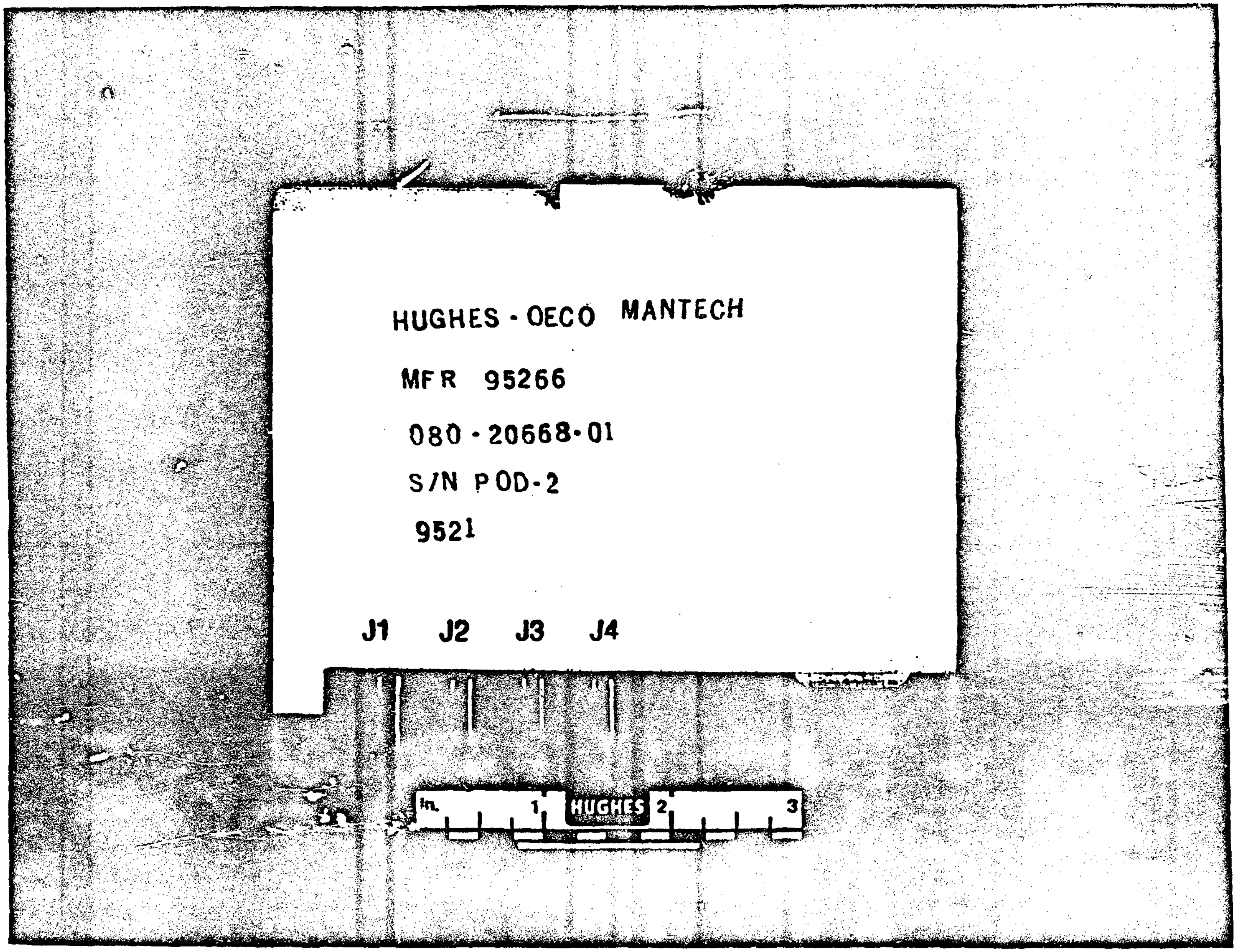
HUGHES - OECO MANTECH
MFR 95266
080 - 20668-01
S/N POD-2
9521
J1
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Figure 6.3-10.

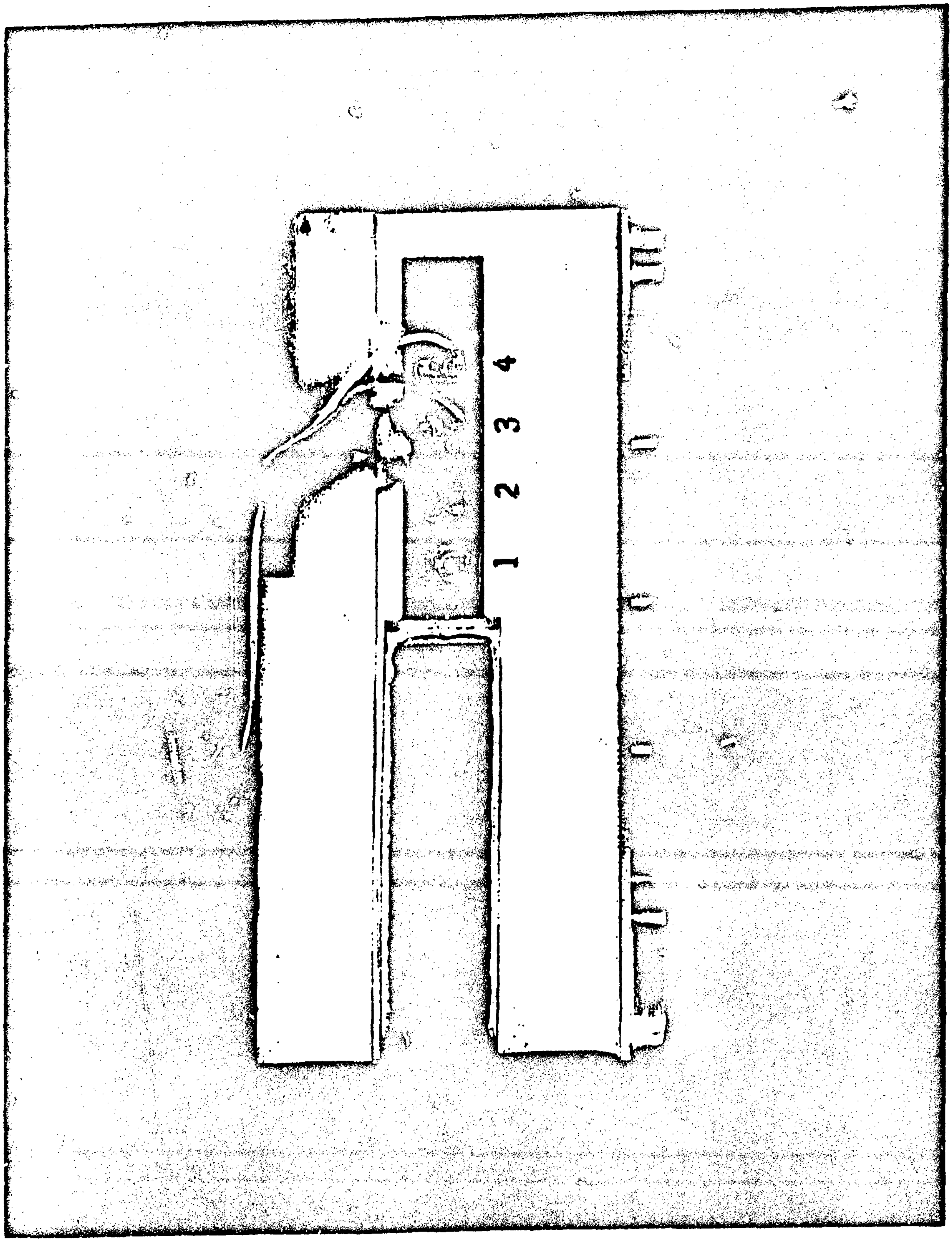

Figure 6.3-11

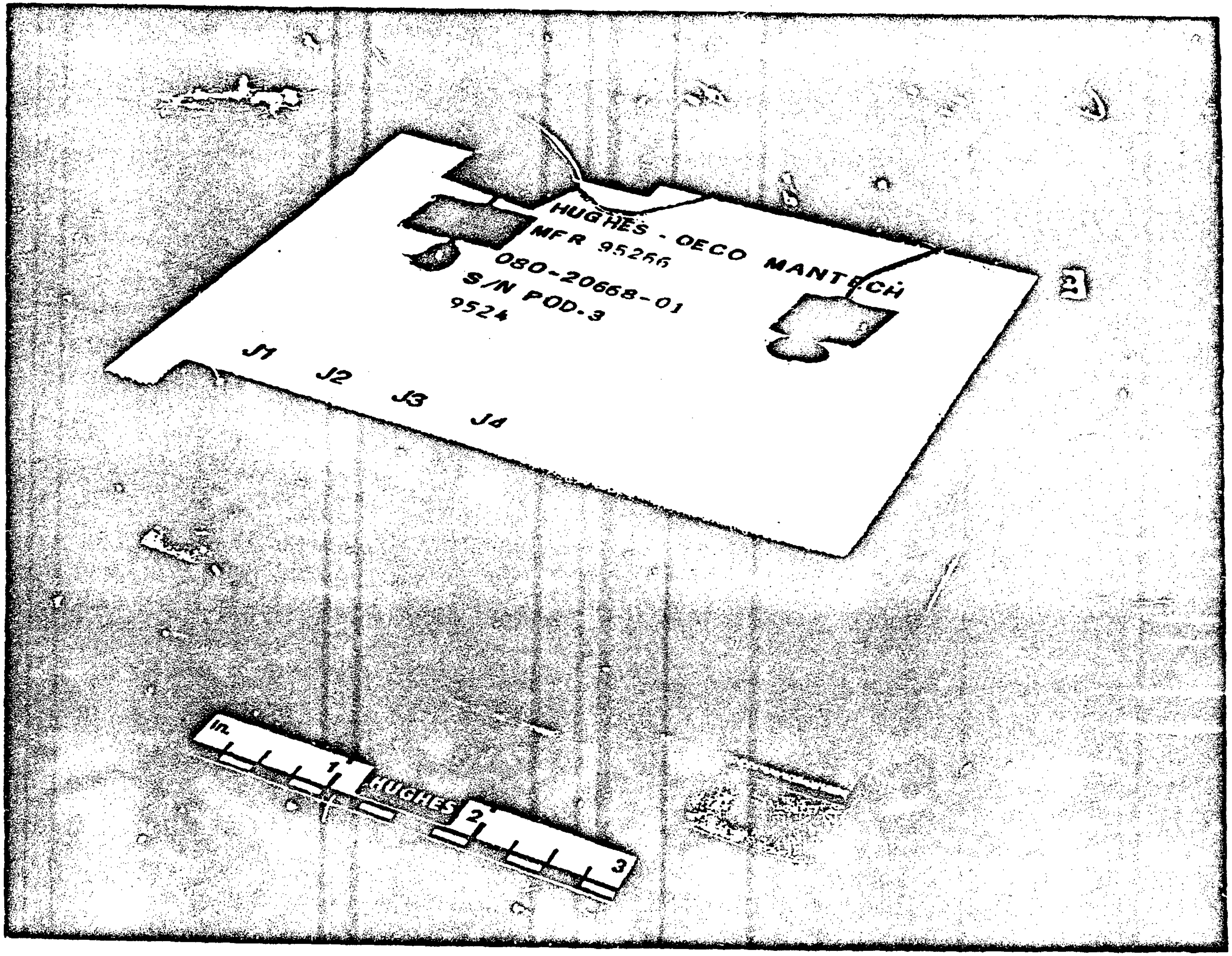
HUGHES - OECO MANTECH
MFR 95266
080-20668-01
S/N POD-3
9524
J1
J2
J3
J4
In.
1
HUGHES
2
3

Figure 6.3-12

7.0 Summary

The program resulted in the development of a systematic approach to the design and fabrication of High Voltage Power Supplies, significant characterization of material and component properties and a better understanding of the test parameters necessary to predict performance and reliability. Accompolishments included:

A "Dock-To-Stock" arrangement with Silicone supplier Grace Specialty Products which allows direct pass-through of the product from receiving to the production floor by establishing both specification limits and Statistical Process Control (SPC) limits as acceptance criteria.

The creation of a systematic design approach, Quality Function Deployment (QFD) which allows all parameters of a HVPS to be optimized for the application. The basic concept can be used to improve the performance of any item of equipment.

Use of Model Test Structures for focussed evaluation of performance at lower assembly levels without the expense and time delay of having to test with actual assemblies. Complimenting this effort is the use of statistical sampling to obtain the maximum information for minimum trials.

Improvements in component diagnostics via use of new ultrasound techniques such as C-SAM.

A clear understanding of the performance and failure mechanisms in high voltge connector assemblies.

Development of a dignostic approach via "costruction review" to compare and evaluate rectifier diodes.

Detailed characteristic evaluation of capacitors, diodes and epoxies from multiple vendors.

Understanding and optimizing test methods to evaluate silicone rubber - a material not easily measured nor well characterized due to its elastomeric nature.

Identification of a prime failure mechanism in high voltage transformers.

In addition to the above, several investigative areas such as surface cleanliness studies, triaxial stress evaluation in silicones, creation of slip planes to allow for thermal mismatches etc., were reported on and complimented the primary work of this program.